SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-80/15

AN INVESTIGATION OF RECYCLING BITUMINOUS PAVEMENTS

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PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

INTERIM REPORT

An Investigation of Recycling Bituminous Pavements

TO: H. L. Michael
Joint Highway Research Project

October 1, 1980
Revised August, 1981
File: 2-8-4

FROM: Leonard E. Wood, Research Engineer
Donn E. Hancher, Research Engineer
Joint Highway Research Project

Project: C-36-210

Attached is an Interim Report, "An Investigation of Recycling Bituminous Pavements" which is part of the HPR Research Project titled, "An Investigation of Recycling Bituminous Pavements". The report was authored by Mr. James McKinney, a Graduate Instructor in Research on our staff under the direction of Professors Donn E. Hancher and Leonard E. Wood.

This report presents a detailed study of the processes used in recycling bituminous pavements. A set of guidelines was developed to assist the pavement engineer in determining if an asphalt pavement is a suitable candidate for recycling. A set of construction guidelines was developed to assist the construction engineer in implementing the recycling method identified by the recycling guidelines. A section of an Indiana highway was selected to demonstrate the use of the guidelines.

This report is offered as fulfillment of tasks D, E, F, G and H of the project and is submitted for review and acceptance by ISHC and FHWA. The remaining tasks are currently active and will have reports covering their findings.

Due to the length of this report, only certain parts are circulated and are identified as Volume 1. Volume 2 carries the balance of the report and will be supplied upon request. The Table of Contents for both Volume 1 and 2 are included so that the reader can determine the total coverage of the report.

Respectfully submitted,

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INTERIM REPORT

An Investigation of [illegible] Bituminous Pavements

TO: K. B. Woods, Director
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October 1, 1960
Revised August, 1961
File: 2-4-6

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This report presents a detailed study of the [illegible] bituminous pavements. A set of guidelines was developed to assist the [illegible] engineer in determining if [illegible] [illegible]. A set of [illegible] [illegible] construction engineer [illegible] [illegible] the [illegible] [illegible] [illegible].

This report is [illegible] the [illegible] for review and [illegible]. [illegible] [illegible].

Due to the length of [illegible] [illegible] [illegible] and [illegible] [illegible] of the report [illegible] [illegible] [illegible] of the figures.

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Interim Report

AN INVESTIGATION OF RECYCLING BITUMINOUS PAVEMENTS

Volume I

by

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Project No.: C-36-21D

File No.: 2-8-4

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission
and the
U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, Indiana
October 1, 1980
Revised August, 1981

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JHRP-80/15		

4. Title and Subtitle	5. Report Date
An Investigation of Recycling Bituminous Pavements - Volume I	Oct. 1, 1980;Revised Aug.1981
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
James L. McKinney	JHRP-80-15
9. Performing Organization Name and Address	10. Work Unit No.
Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, Indiana 47907	11. Contract or Grant No. HPR-1(18)-Part II
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Indiana State Highway Commission State Office Building 100 North Senate Avenue Indianapolis, Indiana 46204	Interim Report Guidelines Phase
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Part of the Study titled "An Investigation of Recycling Bituminous Pavements".

16. Abstract

This report presents a detailed study of the processes used in recycling bituminous pavements. A set of guidelines was developed to assist the pavement engineer in determining if an asphalt pavement is a suitable candidate for recycling. A set of construction guidelines was developed to assist the construction engineer implementing the recycling method identified by the recycling guidelines. A section of an Indiana highway was selected to demonstrate the use of the guidelines.

Due to the length of this report, it has been separated into two volumes. Volume I contains the description of the research topic, plus the recycling guidelines and construction guidelines developed in the study. A sample application of the guidelines plus the research summary is also included. Volume II contains background information on recycling gathered during the study, plus several appendices on recycled mix design and flexible pavement design.

17. Key Words	18. Distribution Statement
Bituminous Recycling, Recycling Guidelines, Recycled Mix Design, Recycled Pavement Design, Pavement Condition Evaluation, Construction Specifications	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	216	

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

The author would like to express his appreciation to the Indiana State Highway Commission, the Federal Highway Administration, U.S. Department of Transportation and the School of Civil Engineering, Purdue University for their financial support of the research program.

The author is especially indebted to his Co-Major Professors, Dr. Donn E. Hancher and Dr. Leonard E. Wood for their guidance, encouragement and advice during the entire study.

The author wishes to thank Mr. Mang Tia for his special assistance on numerous field trips and for his work in the laboratory portion of this study. He would also like to convey his appreciation to Mr. Barry Elkin, Indiana State Highway Commission Research and Training Center for his valuable contributions to this study.

To Professors J. A. Havers and E. J. Yoder of the School of Civil Engineering and J. D. Y. Tse of the School of Management and all others who helped prepare the author for his research, the author offers a sincere expression of gratitude.

Special thanks are given to Ms. Mellanie Boes for her diligent assistance in preparing the thesis.

TABLE OF CONTENTS

VOLUME I

LIST OF TABLES

VOLUME I

LIST OF FIGURES

VOLUME I

HIGHLIGHT SUMMARY

The deplorable conditions that have developed in our highway system is one of the major problems confronting transportation agencies today. Rapidly escalating maintenance and reconstruction costs, coupled with a nearly fixed level of highway funding have contributed significantly to this problem. Asphalt pavement recycling is a viable rehabilitation method that can be used to help solve this serious problem; for recycling can be an economical, as well as an energy efficient rehabilitation alternative. The purpose of this study is to fully investigate asphalt pavement recycling.

Asphalt pavement recycling can be classified into three major areas: surface recycling; central plant recycling; and in-place recycling. This study investigates the type of equipment used, the construction methods employed, as well as the various considerations and limitations associated with each recycling method. Previous recycling jobs were analyzed to determine rates of production, unit costs, unit rates of energy consumption and specific problems encountered during recycling operations.

A set of guidelines was developed to assist the pavement engineer in determining if an asphalt pavement is a suitable candidate for recycling. The recycling guidelines provide a formal method for evaluating the existing pavement structure, identifying its rehabilitation needs, determining the probable cause of distress or failure, as well as identifying an appropriate recycling method. The recycling guidelines also comment on the design of the recycled mixture and the design of the recycled pavement.

A set of construction guidelines was developed to assist the construction engineer in implementing the recycling method identified by the recycling guidelines. The guidelines provide assistance in formulating and evaluating a specific recycling system. Project management decisions, recycling process variability and potential problem areas associated with the proposed recycling system were identified. Guide specifications were synthesized for the major forms of asphalt pavement recycling so that existing specifications can be modified or supplemented for recycling use.

A section of an Indiana highway was selected to demonstrate the use of the recycling guidelines. The existing pavement structure was fully characterized and a recycling rehabilitation method, including mix design and pavement design, was selected and formulated using the procedures developed in this study.

NOTE

Due to the length of this report, the report was divided into two volumes. The basic findings of the research are reported in Volume I, as noted in the Table of Contents. Volume II contains background information on recycling gathered during the study plus several appendices. The Table of Contents for Volume II are shown on the next few pages for the reader's review.

Any person desiring a copy of Volume II of this study can obtain one by contacting the Joint Highway Research Project; Civil Engineering Building; Purdue University; West Lafayette, Indiana, 47907.

TABLE OF CONTENTS

VOLUME II

LIST OF TABLES

VOLUME II

LIST OF FIGURES

VOLUME II

CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

The principal obligation of transportation agencies throughout the United States is the expansion, maintenance and rehabilitation of highway systems under their jurisdiction. However, within the past decade the emphasis has shifted from one of new facility construction to one of maintaining and upgrading existing highway facilities.

Despite the shift in emphasis, the level of service provided by our highway has seriously deteriorated. The deplorable conditions that have developed in our highway system is one of the major problems confronting transportation agencies today. The rapid escalation of costs associated with maintaining and rehabilitating our highway system coupled with the near fixed level of funding available for these maintenance and rehabilitation operations have significantly contributed to the decline of the overall highway condition.

If the highway system is to be returned to an acceptable level of service, rehabilitation methods must be chosen that are not only economically desirable, but that prudently utilize energy and natural resources. Furthermore, since the majority of the roads in this country involve the use of asphalt materials, the rehabilitation method chosen will have to be suitable for asphaltic materials.

Asphalt pavement recycling is one method that can be used to aid in solving the problem of maintaining and rehabilitating the highway system, as

well as dealing with the highway funding problem. Recycling is a viable pavement rehabilitation method that reuses existing materials to upgrade the pavement structure. As such, recycling can be an economical, as well as an energy efficient rehabilitation alternative.

There are many different methods that can be used to recycle asphalt pavements. The choice of a particular method depends on the pavement's original construction, as well as the type and extent of deficiencies to be corrected. The purpose of this study is to investigate the type of equipment used, the construction methods employed, as well as the various considerations and limitations associated with each recycling method. A set of guidelines will be developed that will allow the selection of an appropriate recycling method for a given pavement need. The guidelines will also provide assistance in the formulation and implementation of actual field recycling operations.

1.2 Background Information

1.2.1 Asphalt Use Today

A major component in the construction and maintenance of roads, streets, and highways is asphalt. The first recorded use of asphalt in road construction in this country [13] was in 1870, when a section of a city street, fronting City Hall in Newark, New Jersey, was paved with rock asphalt imported from the Rhone Valley of France. Prior to this time, the use of coal tar as an aggregate binder and waterproofing agent was investigated, but no further practical application of the material was attempted.

In 1876, the United States Congress directed that Pennsylvania Avenue be reconstructed with an all-weather surface. The material selected was asphalt. Some of the asphalt used was naturally occurring Trinidad Lake asphalt, while the rest was rock asphalt. This was one of the first applica-

tions of asphalt cement as an aggregate binder.

By 1903 over 42 million square yards of roads and streets had been paved using asphalt, mostly imported, as the principal cementing agent. However, it was still a relatively uncommon material that was not widely used due to its short supply and high cost. With the advent of the motor car and the associated refining of crude oil to meet the motoring public's fuel demands, this situation changed. For now, asphalt was readily available as a by-product of the petroleum refining process. The growth of the oil industry has been, in part, responsible for the wide use of this product. In 1920, the oil industry refined 1.5 million tons of asphalt cement. By 1973, prior to the decrease in refinery production due to the oil embargo, 35.5 million tons of asphalt were produced.

Before WW II, despite it's early use in paving city streets, the major use of asphalt was in the construction and upgrading of rural, secondary roads. However, since WW II, asphalt has been extensively used in all segments of this nation's highway system. Today there are 3.86 million miles of road in this country, of which 1.89 million miles are hard surfaced [92]. Of this hard surfaced mileage, 94%, or 1.27 million miles, are constructed with asphalt.

This extensive use of asphalt in road construction, is also typical of the makeup of the highway system in the State of Indiana. Within the state, 91% of the hard surfaced roads utilize asphalt or asphalt related products. The Indiana State Highway Commission has 11,203 miles of highway under its jurisdiction [11]. Of this total, 83%, or 9298 miles, are constructed with asphalt.

Like most other structures, asphalt pavements must be properly maintained. Even though these pavements may be properly designed for future

traffic conditions and loads, as well as unique geographic variables and climatic factors, the pavement structure has a finite life. In order for this life to be extended and still provide a desirable level of service to the user (serviceability) the pavement must be routinely maintained and periodically rehabilitated.

This requirement for pavement maintenance and rehabilitation is one of the major problems facing this country's transportation agencies. Since asphalt is the major component in these pavements, any proposed solution to solve these maintenance and rehabilitation problems must, of necessity, concern itself with asphalt pavement maintenance and rehabilitation.

1.2.2 Present Road Conditions

The deplorable conditions that have developed in our highway system is one of the most publicized problems facing the transportation network of this nation today. The Federal Highway Administration conducted a survey of the hard surfaced roads in this country and found that the general overall condition of the road has changed from "good" in 1970, to "fair" in 1975 [142]. This is an alarming decrease in pavement serviceability.

TRIP, The Road Information Program, estimates that 42% of the nation's paved public roads are seriously deteriorated and in need of resurfacing or reconstruction [166]. This amounts to 790,000 miles, out of a total of 1.88 million miles.

The road conditions within the State of Indiana are not much different than those of the nation. 18,323 miles of the 91,662 miles within the state are rated poor [165]. Indiana Highways for Survival estimates that over 40% of the roads are either substandard, poor or just plain bad.

The problem has been widely publicized, particularly with regard to the Interstate Highway System [6,8,54,114,149]. However, the Interstate Highway

System, while accounting for about 20% of the national traffic volume, is relatively insignificant when the 42,000+ miles of the system are compared to the total mileage of all the other types of roads. The serviceability problems on these other types of roads are as bad, if not worse, than on the more highly publicized interstate highways.

There are several major reasons for this decline in highway serviceability. One of the major factors is the increased traffic these roads must carry. Total vehicle mileage is up from 966 billion vehicle miles in 1967 to 1478 billion miles in 1977, a 53% increase [92]. During the same period, the traffic volume on Indiana's roads displayed a similar increase, an increase of nearly 51%. Even more of a factor is that during the same period, truck traffic was up 81%, from 182.4 million miles to 329.5 million miles.

Another contributing factor to the decline in the general condition of the highway pavements is the increased loads these roads must carry. As a result of the oil embargo of 1973, the individual states were under considerable pressure to increase the maximum allowable load a vehicle could carry, as a fuel conservation measure. In all but 10 states, the maximum load limit was raised from 73,280 pounds to 80,000 pounds [6]. Recently, with the political developments in Iran and the associated fuel shortages of 1979, increased pressure was placed on the 10 remaining states to raise their maximum allowable loads limits to a level equal to that of the other 40 states. However, increased loads have an adverse effect on the life of a pavement. The loss of a pavement's serviceability is exponentially related to the maximum allowable vehicular load. Thus, any increase in the load limit that allows heavier trucks on the highways will result in the shortening of the life of the pavement structures involved.

Compounding the problem is the increased number of trucks on the road. The increase in truck traffic can be partially attributed to the decline of the railroads in this country. As more and more miles of unprofitable rail line are abandoned, the transportation of the products that were handled by the railroad is now, for the most part, assumed by the trucking industry. This increased volume is then channeled onto the existing network of highways, thus contributing to the decline in serviceability of these roads.

Another problem is the service life of the pavements. These structures must be maintained if they are to provide a reasonable level of service. It has been estimated by a wide variety of agencies and organizations that this nation's pavements are wearing out 50% faster than they are being repaired [177]. Ideally, the 11,203 miles of state highway within the State of Indiana should be resurfaced every 10 years [165]. In other words, the state should be resurfacing about 1200 miles per year. However, the Indiana State Highway Commission is presently resurfacing only 450 to 500 miles per year.

Related to the service life is the problem of old age. Three quarters of all the miles of roads in this country were constructed before 1940. These roads were built to satisfy needs that have radically changed. The roads were not designed for the volume of traffic, nor the magnitude of loads, or the operating speeds that are being imposed on them today.

Although one might naturally assume that the problem of old age is mostly limited to rural secondary roads, the fact remains that some sections of the Interstate Highway System have already attained a level of service equal to their initial design life [223]. Even though the entire system is incomplete, some of the initial construction has already served its intended function and must be upgraded and rehabilitated. Since these highways do

carry a disproportionate share of the total traffic volume, any serviceability problems are significantly highlighted and reflect on the level of service of the rest of the road mileage.

1.2.3 Highway Finances

The major cause for the decline in the level of service on the nation's highway is the lack of funding that is available to adequately insure that the roads are properly maintained, rehabilitated, and reconstructed. If sufficient money was provided to routinely maintain and periodically upgrade the pavement to satisfy increased service requirements, the resulting system of roads would have a substantially higher level of serviceability. Therefore, one of the major reasons for highway deterioration is that of inadequate highway finances.

In looking at the problem of highway finances, an important concern is the total amount of funds expended for highway needs. All transportation agencies, federal, state, county, and municipal have over the past decade increased the level of funds that are expended on highways. The total amount of highway disbursements in this country has risen from 16.7 billion dollars in 1967 to 29.8 billion dollars in 1977, a 79% increase in total highway expenditures [92]. The corresponding level of increase in expenditures for all highway agencies in the State of Indiana, has also increased 79%, from 355 million dollars in 1967 to 601 million dollars in 1976.

Even though all levels of government have increased the amount of funds that are expended on highways, when the effects of inflation are taken into account and the real level of expenditures are calculated, a decline in real spending is evident. If the total U.S. highway disbursements are analyzed, as a percentage of the Gross National Product, the level of highway expenditures has actually fallen from 2.1% in 1967 to 1.5% in 1979.

If the value of the highway dollar is measured in terms of constant dollars, the total highway expenditures have actually decreased from 16.67 billion dollars in 1967, to 15.94 billion (1967) dollars in 1979.

Another revealing set of statistics is the breakdown of where the highway funds are expended. Of particular importance, with regard to the condition of the roads, are those portions of the funds that are expended for capital improvement, which includes major rehabilitation work, as well as new construction; and those funds expended for maintenance and traffic service, which includes money for routine highway maintenance. Since 1967 total U.S. capital expenditures are up 36%, while total U.S. maintenance expenditures are up 124%. During the same period, total Indiana capital expenditures are up 38%, while total Indiana maintenance expenditures are up 68%.

The percentage of total highway funds that is being spent on administration and other support activities (law enforcement, safety, and debt interest) has dramatically increased at the expense of capital improvement and maintenance expenditures. Since 1967 the total expenditures for administration and other activities has increased 155% in the U.S. and 206% in the state of Indiana. This trend toward allocating more of the total funds to expenditures other than capital improvement and maintenance is evident at all levels of government expenditures.

A study commissioned by the 1976 Indiana General Assembly focused on the needs of the highway system for the 20 year period from 1975 to 1995. The study [238] identified three levels of needs and the associated level of expenditures, in 1975 dollars, required to fullfill these needs. The highest level was real needs, which were defined as those projects that would put the total highway system (state, county, and city) in acceptable

shape to meet traffic needs at the end of 20 years. The lowest level was minimum needs which were defined as those needs that required very little major construction. The improvement associated with this level would be such that the system would be in the same shape at the end of 20 years as it was at the beginning of the period. This level was defined as a "bare-bones" level, below which the system would degenerate further. The middle level, intermediate needs, was a compromise between the two extremes. This level was predicated on the fact that some roads and streets could remain deficient, while others could not. The difference between real needs and intermediate needs would be fullfilled at a variable rate, depending on the type of road involved. The rate varied from fullfilling 100% of the needs of the Interstates, to fullfilling only 25% of the rural and urban collector needs.

The study indicated that 1.159 billion dollars (1975 dollars) ought to be spent annually to fullfill the real needs, while 743 million (1975 dollars) was the annual expenditure level for minimum needs. The intermediate needs would require an annual expenditure of 874 million (1975 dollars). In 1976 total Indiana expenditures were 601 million dollars.

Another study focused on the needs of the county roads in the state of Indiana [35]. The average county road is at a level of serviceability considerably below that of the other types of roads in the state. The county roads make up 72% of the total 91,622 miles within the state. However, of the 601 million dollars that was expended on all highways in Indiana in 1976, only 132.5 million dollars (22%) was expended on the 65,824 miles that make up the county road system. According to the study, by 1980 total county maintenance expenses should exceed revenues by 195 million dollars, 700 million dollars by 1990, and 1 billion dollars by 1995. The study indicated

that the average maintenance and repair expense for county roads (1977) was 1195 dollars per mile, which represents about 63% of the total county road budget. The range of maintenance costs for counties through out the state ran from a low of 393 dollars per mile in Warren County to a high of 3053 dollars per mile in Lake County.

One of the major contributing factors that has caused the level of performance of our highways to decline is the increased cost associated with equipment, labor and materials. A leading all-purpose indicator of increased costs in the heavy and highway construction industry is the Engineering News-Record Construction Cost Index. This index, which combines a theoretical mix of construction materials and common labor costs, illustrates how construction costs vary with time. Since 1967, this index is up from a base of 100 to 290, indicating that on average, highway and heavy construction costs have risen 190% [178].

Another indicator that is more representative of the changes in highway construction costs is the Highway Bid Price Index. This index, constructed by the Federal Highway Administration, FHWA, is composed of bid prices, as reported by state highway departments, for several common, but essential, components of highway construction. The index purports to measure the changes that have occurred in the cost of constructing highways, on average, within this country. This index has increased from a base value of 100 in 1967 to a current value of 295, indicating a 195% increase in highway construction costs over the same period of time [178].

A similar index is constructed using bid price information from projects being built by the Indiana State Highway Commission. This index, the Indiana Highway Bid Price Index, indicates a 238% increase, from a base value in 1967 of 100 to 338 for the end of the second quarter of 1979 [178].

Engineering News-Record also publishes an Equipment Price Index. The index measures the change in the cost of purchasing equipment, as well as renting equipment. For all construction equipment, the index is up from a base value of 100 in 1967 to a value of 256 in July of 1979. Since highway construction is a larger user of equipment, this would indicate that the equipment portion of the highway costs has increased 156%, a relatively modest gain, when compared to other cost components [178].

The component of highway construction costs that has shown the most dramatic increase since 1967 is materials. The FHWA, through information supplied by state highway departments on bids they have received, has developed a Surfacing Index that measures the increased costs associated with paving a highway. This index, which takes into account Portland cement concrete, as well as bituminous concrete, has risen 205% since 1967 [178].

Within the Surfacing Index, the cost of bituminous concrete has risen more than that of the Portland cement concrete. The FHWA reports that the average bid price for one ton of bituminous concrete, in place, has risen from $6.47 per ton in 1967 to $20.72 per ton for the second quarter of 1979.

One of the major reasons for this increased bituminous concrete price is the asphalt that is needed to manufacture the material. Even though asphalt cement normally comprises only 5 to 6% of the total materials in the mix, its cost has risen from 20 dollars per ton, for paving grade asphalt in Chicago, in 1967 to $100 per ton in 1979 [122]. This represents a 5 fold increase in the cost of the basic cementing agent.

A similar, but less dramatic, increase is shown in the rise of the price of 1 gallon of an asphalt emulsion, RS 1, from $.12 per gallon in 1967 to $.40 per gallon in 1979 [122]. This represents a 233% increase in cost, even though a gallon of this material is made up of about 60% asphalt and

40% water.

Another major factor related to highway financing is the level of revenues that are generated to finance the highway programs. Most of the funds for highway expenditures come from user fees such as taxes, licensing and registration fees. The fuel taxes are of two types - a uniform federal tax that is the same in all states, and a state tax that varies according to local desires and legislative action.

The problem with the generation of highway revenues by user fees is that the source of these funds have remained essentially fixed over the past two decades. The major portion of the federal highway taxes that are collected is due to the 4¢ per gallon tax on gasoline. This tax rate has remained constant at the 4¢ level since 1959.

The situation, with regard to the state tax, is essentially the same as the federal tax. The State of Indiana collects 8 cents per gallon of gasoline. This tax has only been increased once during the past 21 years, when in 1969 it was raised from 6 cents to 8 cents per gallon. However, the 1980 Indiana General Assembly passed a measure changing the gas tax from a flat rate of 8 cents per gallon to an ad valorum rate of 8 percent.

The third major source of revenue is the fees that are charged for various licenses and permits, as well as, vehicle registration. As is the case with the gas tax revenues, the amount of money generated by these fees, in the State of Indiana, has remained essentially fixed over the past two decades.

Of significant importance regarding revenues generated from fuel taxes, is the fact that, although the cost per gallon of fuel has nearly tripled in the past decade, the rate of tax on the fuel has not changed, to any significant degree. Thus, the only increased revenue that can be generated from

user fees is that which comes from increased fuel consumption and/or increased vehicle registration.

Several factors have had a major effect on the generation of highway funds. Of recent concern is the decrease in the amount of fuel being consumed per vehicle. The average amount of fuel consumed by a vehicle in the United States rose from 811 gallons per year in 1967 to 880 gallons per year in 1973 [92]. The fuel consumption for vehicles in the State of Indiana followed a similar trend over the same period of time, with use up from 850 gallons in 1967 to 972 gallons per vehicle in 1973. However, since 1973 fuel consumption has dropped off dramatically to a national average of 804 gallons per vehicle in 1977, while in Indiana the average use has dropped to 884 gallons per vehicle. This drop, both nationally and within the state of Indiana, can be attributed to many factors. The fuel shortages generated by the oil embargo of 1973, as well as the resulting higher prices, certainly has had a restraining effect of vehicle fuel consumption. The Federal government through its mandatory 55 MPH national speed limit and the congressionally dictated automobile fuel economy standards has also contributed to lower per capita fuel usage. Of even more consequence is the national trend of automobile owners to trade their larger, fuel inefficient vehicles in for smaller, more readily available vehicles that have better gas mileage capabilities. All of these factors have combined to raise the national rate of fuel consumption from 11.85 miles per gallon in 1973 to 12.34 miles per gallon in 1977.

Obviously, this decrease in the amount of fuel consumed per vehicle, in conjunction with the steady tax rates, have combined to dramatically affect the amount of highway revenue available. Nearly all the increased level of revenue generated is attributable to the increased vehicle registration in

the country. Since the major portion of the highway expenditures are made from user generated funds, the problem becomes obvious. More money needs to be expended to rectify the declining road serviceability problem. However, due to constant level fuel taxes and lower per capital fuel consumption rates, revenues have remained nearly constant.

One method to increase revenues is to raise the user fees, particularly the gas taxes. However, with the recent anti-tax sentiment by property owners across the country and the national trend to maintain taxes at a constant level, any effort to raise highway taxes has encountered stiff opposition.

Another method to increase revenues is through the use of debt-financing. Many states throughout the nation have turned to the sale of revenue bonds as a partial solution to supplement user generated highway revenues [126]. However, with the exception of the Indiana Toll Road and a few streets, Indiana's highways are user financed. Since the state incurred tremendous losses during the construction of a canal system in the 1850's, Indiana has been prohibited from debt-financing any capital improvement projects. As a result, 98% of the cost of the highways in Indiana are non-debt funded.

Of significant importance to the state of Indiana is the return of federal funds. Historically, Indiana has nearly always received less than a dollar for every dollar sent to Washington. Indiana has consistently ranked near the bottom of the list for return of federal funds.

The money that is returned from the federal government is another method to bolster locally generated revenues. However, most of the money that returns from the federal government carries very exacting stipulations of where it can be used. A good example is the funding of Interstate High-

way construction. The Surface Transportation Assistance Act of 1978 provides for about 45% of the Title I, Highways, funds to be used for Interstate Highway completion [176]. Since Indiana took upon itself to finish its portion of the Interstate Highway system early, it receives none of this 45% portion, even though a part of it was generated within the state.

Contributing to the problem is the diversion of highway revenues to other uses. The Surface Transportation Assistance Act of 1978 authorized increased expenditures for public transportation. During the four year life of the authorization, Title I expenditures for highways is to decrease from 7.4 billion dollars in FY 1979 to 7.1 billion in FY 1982, while Title III expenditures, Public Transit, is to increase from 3.2 billion dollars to 3.7 billion dollars during the same period [176]. This diversion of funds from state highway uses to mass and public transit uses may be necessary, however it does nothing to alleviate the problem of poor roads.

It is quite obvious that the general condition of the highways is, in part, a function of the amount of money expended on the highways. The current highway deficiencies could be corrected with the expenditure of a sufficient level of funds. A preventative maintenance program that would not allow significant pavement deterioration could be instituted, given a certain level of funding. The reason these measures have not been instituted is due to the limited funds that are available. Highway agencies throughout the country have been caught in the dilemma of trying to maintain and improve road conditions with a fixed level of funds, derived from unchanging user fees, while the real value of these funds is being rapidly eroded due to the impact of inflation.

1.2.4 Energy Considerations

Highway construction, as well as reconstruction, is a high energy business. The nature of the work and the equipment used, mandates that large quantities of fossil fuel be consumed. This poses another problem to the highway systems in this country. Since the oil embargo and the curtailed imports of petroleum products into this country of recent years, the construction industry, which once nearly ignored the energy requirements of its operations, now has become acutely aware of fuel requirements. Threatened by partial or total disruption of needed supplies, as well as increasing prices, contractors are becoming more energy conscious. Highway agencies are also starting to evaluate alternative designs, not only for economical desirability, but also for efficient use of energy.

A study by the Transportation Research Board of 400 to 500 highway contractors produced the fuel consumption figures shown in Table 1-1 [74]. These figures show the magnitude of fuel required per unit of production of a variety of highway construction activities, as a function of the job conditions.

The Asphalt Institute has published a detailed examination of the energy requirements for constructing different types of pavements [64]. This study analyzes the energy needs required for manufacturing all materials, hauling, placing, and compaction of these materials, and, where pertinent, energy requirements ancillary to the basic paving operation. All energy requirements are reported in terms of BTU's, to alleviate the problem of different energy values for different fuels. Energy requirements to manufacture and place different types of pavements are shown in Table 1-2. Energy requirements for typical pavement designs are shown in Figure 1-1. The major advantage of an analysis of this kind is the ability to evaluate a pro-

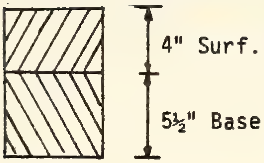
Table 1-1 Fuel Useage Factors

Item of Work	Units	Diesel			Gasoline		
		Low	Average	High	Low	Average	High
Excavation	Gal/CY						
Earth		.27	.27	.30	.11	.15	.21
Rock		.37	.39	.42	.17	.18	.22
Other		.33	.35	.38	.15	.16	.18
Aggregates	Gal/Ton						
On Site Production		.25	.28	.36	.08	.09	.11
Aggregate Base							
0 - 10 mile haul		.24	.27	.33	.22	.24	.28
10 -20 mile haul		.35	.42	.54	.27	.39	.49
Asphalt Concrete	Gal/Ton						
Production		.17	.24	.35	.07	.14	.18
Hauling							
0 - 10 mile haul		.28	.33	.34	.35	.43	.53
10 -20 mile haul		.30	.49	.56	.35	.58	.89
Placement		.06	.14	.20	.08	.14	.22
Portland Cement	Gal/CY						
Production		.15	.28	.45	.12	.15	.21
Hauling		.33	.48	.67	.52	.52	.52
Placement		.13	.22	.31	.14	.23	.38
Structures	Gal/$1000	10	19	25	10	22	45
Misc	Gal/$1000	10	19	30	10	19	30

Table 1-2 Energy Consumption of Paving Materials, In-Place (64)

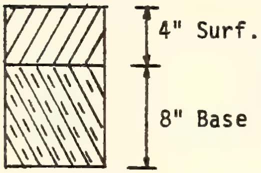
Crushed Stone Base	
Produce Crushed Stone	70,000 BTU/Ton
Haul - 17½ miles	149,450
Spread and Compact	17,000
	236,450 BTU/Ton
Portland Cement Concrete	
Portland Cement	998,630 BTU/Ton
Aggregate	116,150
Plant Operations	5,730
Haul - 10 miles	42,700
Place	2,510
	1,165,720 BTU/Ton
Emulsified Base	
Asphalt	80,810 BTU/Ton
Aggregate	129,190
Plant Mix	6,630
Haul - 15 miles	64,050
Spread and Compact	16,700
	297,380 BTU/Ton
Asphalt Concrete	
Asphalt	54,580 BTU/Ton
Aggregate	133,400
Plant	243,090
Haul - 15 miles	64,050
Spread and Compact	16,700
	511,820 BTU/Ton

Full-Depth Asphalt Concrete



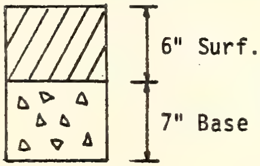
surf: 4 in. @ 27,800 BTU/sy-in	= 111,200 Btu
base; 5½ in. @ 27,800 Btu/sy-in	= 152,900 "
Total	= 264,100 Btu/sy

4 inch Asphalt Concrete plus 8 inch Emulsified Asphalt Base



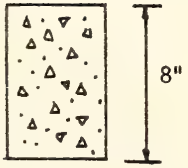
surf: 4 in. @ 27,900 Btu/sy-in	= 111,200 Btu
base: 8 in. @ 15,600 Btu/sy-in	= 124,800 "
Total	= 236,000 Btu/sy

6 inch Asphalt Concrete plus 7 inch Crushed Stone Base



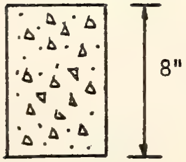
surf; 6 in. @ 27,800 Btu/sy-in	= 166,800 Btu
prime: 0.25 gal/sy	= 12,400 "
base: 7 in. @ 11,500 Btu/sy-in	= 80,500 "
Total	= 259,700 Btu/sy

8 inch Portland Cement Concrete



8in. @ 67,700 Btu/sy-in	= 541,600 Btu/sy

8 inch Reinforced Portland Cement Concrete



conc: 8 in. @ 67,700 Btu/sy-in	= 541,600 Btu
Transverse steel	
8 in. @ 2410 Btu/sy-in	= 19,280 "
Longitudinal steel	
8 in. @ 23,110 Btu/sy	= 184,880 "
Total	= 745,760 Btu/sy

Figure 1-1 Energy Requirements for some Typical Pavement Sections (64)

posed pavement in terms of the magnitude of energy that is inherent in the design. In the future an energy consumption criterion may become important in selecting alternative designs, as the cost criterion is today.

With increasing energy costs and decreasing availability of fuels, energy has become a significant problem in highway construction operations. Any reconstruction or rehabilitation work must consider the energy ramifications inherent in each proposed alternative.

1.2.5 Other Considerations

The present condition of the highway system has produced several other problems. According to a study by the Indiana University Institute for Research in Public Safety, hazardous road defects were a principle cause of 21% of the 10,500 traffic accidents that occurred during a 42 month period [165]. In the State of Indiana, the second leading cause of accidents (behind human error) was the bad, unsafe, physical condition of the roads - chuckholes, pavement edge drop-offs, blind intersections, sharp curves, steep dips and crests. Most of these deficiencies can be attributed to the decline in road serviceability.

Another problem associated with the bad condition of the roads is the problem of liability [230]. Negligent maintenance is least likely of all highway functions to be immune from liability. The courts have tended to consider the maintenance phase of highway operations as routine housekeeping, necessary in the performance of normal day to day government administration. Highway maintenance is exercised at the operational level and even though discretion to some extent is involved, the discretionary decisions to be made are not policy-oriented. Where a claim arises out of negligent maintenance, the state or the public official or the employee is most likely to be held liable.

Given the fact that the majority of the roads in this country involve the use of asphaltic products, and given the fact that the general level of service being currently provided by these highways is less than desirable, any method or solution advanced to deal with pavement maintenance or reconstruction must, of necessity, deal with maintaining or reconstructing asphalt pavements. These rehabilitation methods should deal with the problem of economics, as well as energy consumption. These methods should return the pavement structure to a safe and efficient level of service.

1.3 Maintenance and Rehabilitation Methods

Today a wide variety of different operations exist that can be used to treat the pavement deterioration problem. The maintenance and rehabilitation options available to the pavement engineer are quite extensive. A listing, by no means complete, for asphalt pavements, might list these options [15,17,19].

1. Do nothing - Self explanatory.
2. Patching - Removal of defective material to a depth where sound material is encountered and replacement with higher quality material.

   Deep Patches - Permanent

   Skin Patches - Temporary
3. Crack Filling - Filling of crack or pavement separation with bituminous material.
4. Sealing - Thin surface treatment.

   Aggregate Seal - Essentially a single application of asphalt followed immediately by a single layer of aggregate, of uniform size.

   Emulsion Slurry Seal - Mixture of slow setting asphalt emulsion, fine aggregate and mineral filler and water.

   Sand Seal - Application of asphaltic material covered with fine

aggregate.

5. Surface Treatment - A broad term embracing several types of asphalt and asphalt-aggregate applications, usually one inch thick or less.

   Single Surface Treatment - A single application of asphalt followed immediately by a single layer of aggregate of as uniform size as practical.

   Multiple Surface Treatment - Two or more surface treatments placed one on the other, the aggregate size of the second application being approximately 1/2 of that of the first.

6. Overlays - One or more courses of asphalt construction placed over the existing pavement to correct surface and structural deficiencies.

   Level and Wedge Courses - A course of variable thickness used to eliminate irregularities in the contour of existing pavements prior to subsequent treatment or construction.

   Thin Overlay - A course of uniform thickness, applied to structurally adequate pavements to correct surface deficiencies and renew the surface.

   Thick Overlays - A course of sufficient thickness that is applied to existing pavements to strengthen the pavement to accommodate the traffic using it for the design period.

7. Reconstruction - Total removal and replacement of some, or all, of the pavement structure with new materials. Deficient components of the pavement are rebuilt as needed.

1.3.1 Federal Rehabilitation Programs

Many agencies have struggled with the problem of how to maintain and rehabilitate their highway systems. In an effort to encourage these agencies in this vital work the federal government first allocated highway trust funds to finance reconstruction work in 1976. The program developed was

called the 3-R program for Resurfacing, Restoration, and Rehabilitation [118]. The 1976 Federal-Aid Highway Act redefined new construction to include 3-R work [69,93]. The intent was to permit use of federal funds to improve highways, specifically Interstate Highways, without making costly alignment and geometry changes, in order to quality for federal funding. The Act set aside $175 million dollars for FY 1978 and FY 1979, to be apportioned to the states, solely on the basis of the Interstate mileage within the state.

The Surface Transportation Assistance Act of 1978 made the 3-R Program permanent with a level of funding of $175 million dollars of FY 1980 and $275 million dollars for both FY 1981 and FY 1982 [176]. The apportionment formula was changed to a system where three quarters of the funds are based on the Interstate lane-miles in use for 5 or more years and the other quarter based on the vehicle miles of travel on these lane-miles. The funding participation is 75% Federal and 25% state.

The 1978 Surface Transportation Assistance Act also mandates that at least 20% of each state's apportionment for primary and secondary systems must be used for resurfacing, restoring, and rehabilitating existing highways. For the primary system this means a minimum of $310 million dollars for FY 79 and up to $360 million for FY 1981. The secondary system expenditures will rise from $100 million in Fy 1979 to $120 million in FY 1981.

1.4 Recycling as an Alternative

Another method that has been used as part of the 3-R program, and which is a major method for maintaining and rehabilitating asphalt pavements, is that of recycling - the concept of removing the existing pavement material, recovering the useful components, and reconstructing a new pavement that will perform at a higher level of service for an extended period of

time.

One of the incidental benefits of the extensive use of asphalt in our highway system is the ability to reuse, or recycle, nearly all of this asphalt. Asphalt pavements have been reprocessed in a variety of ways and reutilized in nearly the same manner that new asphalt concrete is used. Bill Swisher, President of CMI, stated in a May 11, 1978 press conference:

> "Billions of tons of asphalt paving material are lying dormant in the worlds' deteriorated street and highway network, creating an "internation asphalt bank". Each year, tax payers make deposits in this bank by funding repeated overlays of new pavement to cover up potholes, surface cracking and deterioration."

Recycling is a viable pavement rehabilitation alternative. The main arguments in favor of recycling are those that deal with the previously mentioned problems that our highways are facing today: the problems of deteriorating road conditions, low levels of funding and expenditures, and severe effects of inflation on the highway programs around the country.

Basically, the advantages for recycling can be divided into the following categories:

1. Natural Resources
2. Energy
3. Ecology
4. Pavement Geometry
5. Recycled Product
6. Economics

1.4.1 Natural Resources

The major advantage of recycling asphalt pavements is the ability to reuse natural resources which, because of their non-renewable status, have risen dramatically in price and become more difficult to obtain.

Each ton of asphalt pavement, in place, represents about 1200 pounds of well-graded coarse aggregate, 680 pounds of well-graded fine aggregate and about 120 pounds or about 14 gallons, of asphalt cement. These materials can be salvaged and reused.

The aggregate portion should show very little, if any, wear as it is recycled. The gradation that was built into the original mix, at the original time of construction, should still be there. The aggregate fraction of the mix is totally reusable.

A 1976 report, published by the U.S. Air Force Civil Engineering Center [115], identified geographic areas of aggregate shortages in this country. The study also pointed out the fact that most metropolitan areas are experiencing some form of aggregate shortage. According to M. J. Hensley, District Engineer of the Asphalt Institute, our requirement for conventional aggregate will grow to 4 billion tons per year by 1985, up from 1.8 billion tons per year in 1970, and 2.5 billion tons per year in 1975 [185]. Recycling asphalt pavements can help meet this increased aggregate demand.

The other major ingredient in bituminous concrete is the cementing agent, asphalt. Although this material represents a small percentage of the total mix weight or volume, it represents the largest cost of the mix. Asphalt is a product of crude petroleum distillation, and as such, is subject to the same price increases and potential shortages that other oil-related products have experienced in recent years. Any method that can reduce the consumption of new asphalt will, necessarily, save natural resources. Although no acute shortages have been experienced in obtaining new asphalt, the potential for shortages exists. With increased emphasis on altering the residual fractions to a higher degree, asphalt may be in shorter supply with resulting higher prices.

Recycling provides a means of reusing the asphalt that is already in place in the road. A single mile of pavement consisting of three lifts contains the asphalt that was obtained from 44,958 barrels of crude oil [90]. By recycling this asphalt, the need to refine the crude oil for road construction purposes is significantly reduced. Even though the asphalt in the pavement has aged with time, methods exist by which the original characteristics and properties of the asphalt can be restored. The material may be reused in other applications, thus conserving natural resources, and is less subject to shortages and price increases.

1.4.2 Energy

The process of manufacturing asphalt concrete and constructing asphalt pavements is an energy intensive business. The Asphalt Institute in a study of the energy demands for various types of pavement [64], found that the manufacturing and transportation of the raw materials - aggregate and asphalt - represented nearly 35% of the total energy demand required to produce and place asphalt concrete. The energy required to produce a 42 gallon barrel of asphalt is about 52,500 BTUs. Another 52,500 BTUs is required for further processing and handling, resulting in a total energy input of 105,000 BTUs per barrel. With 42 gallons per barrel and 235 gallons per ton, an energy demand of 587,500 BTUs is required to manufacture a ton of asphalt cement. According to the Asphalt Institute, the average haul distance for transporting asphalt cement from the refinery to its point of use is about 50 miles. This haul distance represents another 504,000 BTUs of energy demand to provide the raw materials to a contractor. If this transportation energy is added to the manufacturing energy, a total of 1,091,500 BTUs per ton is represented by the raw material.

The energy required to process and transport the aggregate that is used in the asphalt concrete is calculated in a similar manner. The generally accepted figure for energy required to produce crushed stone is 70,000 BTUs per ton. Natural or uncrushed aggregate, which requires a minimum of processing, is assumed to require about 2 horsepower hours per ton of material processed. Assuming .06 gallons of gasoline per horsepower hour, the processing is equal to about 15,000 BTUs per ton. Assuming an aggregate haul distance of 10 miles, and an aggregate blend of 65% crushed stone and 35% processed sand, the typical aggregate energy demand is 140,420 BTUs per ton of raw material [64].

If the asphalt fraction of the total mix is assumed to be 5% and the aggregate component 95%, the manufacturing and transportation energy represented by the raw material blend of the asphalt concrete is 187,980 BTUs per ton.

The percentage of total energy represented by the manufacture and transportation of raw material components of emulsified asphalt bases is even larger - 71% of the total demand, to construct an emulsion base. The Asphalt Institute estimates that it requires about 2100 BTUs per gallon to produce an emulsion (MS-1). With 241 gallons per ton of emulsion and an average haul distance of 50 miles from the point of manufacture to the point of use, a ton of emulsion requires the expenditure of 1,010,000 BTUs. If the same aggregate blend that was used in asphalt concrete (65% crushed and 35% processed sand) is used in the base formulation and if 8% emulsified asphalt and 92% of the aggregate blend is used, the resulting energy represented by a ton of the raw materials in the emulsified base is 210,000 BTUs [64].

For a plain, crushed stone base, the manufacture and transportation of the aggregate represents 93% of the total energy required to construct the base. Crushed stone requires, on the average, 70,000 BTU per ton to process. Assuming an average haul distance of 17.5 miles, the energy required to transport the crushed stone to the point of use is 149,450 BTU/ton. Thus, the total energy represented by the raw materials used in a crushed stone base is 219,450 BTU/ton [64].

Through the recycling process most of this energy needed to manufacture and transport raw materials for pavement reconstruction is eliminated because old materials, that were previously manufactured, are reused. Energy must be expended to reprocess the salvaged material into a form which can be recycled, but in nearly all recycling methods, substantially less energy is required for reprocessing than for manufacturing new materials. Thus, recycling can result in a substantial energy savings over conventional, new material construction.

1.4.3 Ecology

Recycling is an ecologically desirable construction method that emphasizes the positive environmental aspects of reusing a non-renewable resource. Asphalt pavement recycling is in the national interest because, at a time when the availability of depletable resources are causing raw material shortages, it reuses, instead of wastes valuable pavement materials.

In the past, when an existing highway was reconstructed, either the existing pavement was overlayed with new material or it was removed and replaced with new material. If the old pavement was removed, it was either disposed of along the side of the road or hauled to a land fill area. Neither of these alternatives is desirable today. Road side dumps of wasted pavement are unsightly and, in some cases, illegal. Today in some metropol-

itan areas disposal charges for dumping waste pavement in landfills can run as high as $18 per ton [16]. Recycling can eliminate both of these problems.

Furthermore, recycling is highly encouraged by the Federal government as a responsible solution to highway problems and the general handling of waste products. In its directive of September 28, 1976, the Federal Highway Administration, through Notice N5040.22, "Recycling of Pavement Materials", "highly recommends and encourages" asphalt pavement recycling as a rehabilitation method that is desirable for the paving industry today.

1.4.4 Geometry

A major reason for recycling, particularly in urban areas, is the benefits that can be achieved by maintaining or improving the pavement geometry. Typically, in an urban situation where successive overlays have been applied to rectify pavement distress problems, curb reveal and the actual curb lines have been lost, along with the associated storm drainage capacity. To correct the problem, either the existing curbs must be raised or be rebuilt, a costly proposition. However, in most urban situations the drainage problem has been neglected.

Overlays can also cause cross-slope problems with the pavement surface. In an effort to maintain curb lines and curb reveal, the overlay is feathered out at the curb line and a full thickness is applied at the center of the road, resulting in a dramatically emphasized crown. If material is removed from the vicinity of the curb prior to overlay, in an effort to obtain full overlay thickness, yet maintain curb reveal, the cross-slope problem is further accentuated. In residential areas severe crowns in the roadway cross-slope can cause the undercarriage of automobiles entering residential driveways to drag on the pavement surface. Recycling can help eliminate

these cross-slope problems.

Another problem with building on top of an existing pavement is the need to insure that a smooth transition is maintained from the overlay to the shoulder surface, without any abrupt dropoff. In most cases when conventionally overlaying the pavement and not resurfacing the shoulders, a wedge and level course should be applied to the shoulders to correct the abrupt vertical dropoff that is created at the overlay - shoulder intersection. The alternative method for dealing with this problem is to import new material in an effort to build up the shoulders to the level of the pavement overlay.

Vertical clearance is another problem that must be considered in pavement reconstruction. The clear distance between the pavement surface and overhead constructions must be maintained in tunnels and under bridges and viaducts. Overlay buildups can cause critical clearance problems that can be extremely expensive to remedy. This same problem exists with regard to the vertical adjustments of guard rails and other safety structures. With multiple overlays creating a substantial increase in pavement elevation, costly adjustments must be made to maintain the required vertical adjustments of these structures in relation to the pavement surface.

1.4.5 Product

Some preliminary work has been undertaken to examine the final product of the recycling process. Although the concept of recycling is not new, the acceptance of recycling as a rehabilitation method is just beginning to develop. Because of this recent tentative acceptance, little data is available regarding the long term performance of the recycled product. However, some preliminary studies indicate that the recycled product may be at least equal to, if not better than, a new virgin material product.

The obvious benefit of recycling is the ability to identify problem areas that have developed while the pavement was serving its original function. Structural problems in the road can be identified and corrected while the pavement is being recycled. Deficiencies in initial mix design can also be corrected. Excessive bitumen content can be remedied by the addition of virgin or base aggregate. Aggregate gradation deficiencies can be corrected as desired. Viscosity (penetration) and ductility characteristics of the binder may be changed, as required, by the addition of new asphalt and/or rejuvenating agents.

One of the most obvious concerns associated with reworking old asphalt pavements is the oxidation that the binder has undergone during its service life. Coons and Wright [47] studied a 2 inch thick layer of aged pavement (18 years old) and found that the majority of oxidation occurs in the top 1/4 inch layer, where only 45% of the original penetration and 33% of the ductility is retained. However, for the entire 2 inch sample, taken as a whole, 71% of the penetration and 83% of the dutility is retained over the pavement life.

Original binder properties that are lost (in varying degrees as a function of the distance from the pavement surface) in the oxidation process can be recovered through the use of agents that replace resins lost in the aging process. Thus, the old binder can be softened and reconstituted to approximately its original characteristics and be reused in the manner for which it was originally intended.

If the shale content of the original aggregate fraction of the asphalt mix was near the upper limit, recycling can be a distinct advantage with regard to pavement life [86]. The negative effect that shale has on pavement service life will already have been neutralized by the existing residual as-

phalt content and exposure to weather. Thus, if the shale is to be reused, a more durable pavement should result.

If the pavement distress that led to reconstruction was due to low temperature cracking, recycling will produce bituminous mixes that will have less tendency to crack in the future [217]. The reason that recycled pavements develop resistance to low temperature cracking is the oxidation that the asphalt cement has already undergone. Oxidation reduces asphalt temperature susceptibility characteristics and will improve low temperature performance of the pavement. This process of oxidation by aging can be likened to 'air-blowing' in the refining process that results in a less temperature susceptible asphalt.

Another recycling benefit is in the area of aggregate - asphalt adhesion. If the binder strips from the aggregate when the asphalt concrete is initially produced, there is less of a tendency for this to reoccur when the same materials are recycled [217]. This is particularly true for hot mixes. Prolonged contact of asphalt and aggregate while in service on the road is known to improve bond at the interface of aggregate and asphalt.

The reological properties of bitumen from recycled pavement materials appear to be better than the reological properties of new hot mixes. Recycled asphalt concrete mixes do not appear to age as fast, nor are they as "tender" as pavements constructed with new asphalt. Betensen [31] studied a recycled pavement in Utah over a three year period from 1975 to 1978 and found that the binder in the recycled mix appeared to be increasing in viscosity, as a function of time, at a rate slower than the rate of viscosity change displayed by a virgin asphalt.

The preceding material properties have led many researchers to believe that recycled pavements will perform as well as, if not better than, new ma-

terial pavements.

1.4.6 Economics

One of the major criteria that determines whether a new process will be accepted or not, is economics. If the recycling of asphalt pavements can demonstrate an economic advantage over new material construction, recycling can be accepted as a viable rehabilitation alternative.

The main area of economic advantage that recycling appears to have over new material construction is in the area of raw materials required for the project. Since the recycling process reuses materials already on the roadbed, little or no new materials have to be purchased. The salvaged material removed from the pavement has an intrinsic value which can be attributed to the asphalt and aggregate components of the old pavement. This value is related to the cost of new raw materials. Current estimates of the value of this salvaged material are conservatively placed at $10.00 per ton [122]. With new aggregate priced at $4.60 per ton and new asphalt at $100.00 per ton, a ton of salvage material, in terms of virgin material prices, is $4.00 for the aggregate fraction and $6.00 for the asphalt fraction. With current hot mix prices ranging from $18 to $20 or more per ton (in place), a substantial amount of money could be expended to reprocess the old pavement into a new form and replace it on the roadway, and yet still realize a cost savings over new material construction. In general, as long as the cost of removing and reprocessing the old pavement is less than the cost of purchasing new virgin materials, recycling should be economically competitive with new material methods.

Transportation costs are another area of consideration that should be investigated when evaluating the economical aspects of recycling. With recycling, the requirement to transport raw material from the point of

manufacture to the point of use is either substantially reduced or eliminated, which can result in large costs savings. This is particularly true for certain areas in this country where, because of their remoteness, extremely long haul distances are required to import either aggregate, or asphalt, or both. The normal recycling process either removes the old pavement and transports it to a central processing plant (usually located in close proximity to the project), or processes the material on the roadbed itself. In either case, the transportation requirements are substantially lower than they would be with new material construction. With fuel and machinery costs rapidly escalating in price, a decrease in the transportation requirements, such as is the case with recycling, can mean a substantial cost savings to the project.

Since the materials that are to be recycled are already on the roadbed, recycling provides an expedient method to avoid material shortages and raw material price increases. Salvaged pavements are not subject to the same disruption of supply that new materials can suffer. Work stoppages and strikes at raw material producing facilities should not cause material shortage problems for reclaimed asphalt pavements. Since the materials were previously purchased at some time in the past, little or no problems are encountered with rapidly escalating raw material prices in recycling asphalt pavements.

Asphalt pavement recycling can be a simple, economical process that utilizes available equipment and technology already known. This in itself can result in a cost savings. With simpler operations, along with the resultant ease of project supervision, recycling can be less costly than conventional new material construction.

1.5 History of Recycling

Recycling of asphalt pavement is not a new concept. According to the National Asphalt Paving Association (NAPA) [183], one of the first written references to recycling was that of the Warren Brothers' efforts in 1915. Warren Brothers, in their asphalt plant sales brochure stated that their plants -

> "heated and reworked existing sheet asphalt pavements with excellent results and considerable savings in the cost of the resultant mix"

This type of work continued until the early 1930's. According to historical records there was a considerable amount of recycling done in the urban areas of the Eastern United States during this period.

However, as new oil refineries were built, asphalt supplies increased to the point where the prices of new asphalt dropped below the cost to recycle the existing asphalt - a trend that has recently reversed itself.

Recycling efforts in Singapore in the 1930's have been documented by Taylor [225]. The process, referred to as "Recondo", involved reclaiming sheet asphalt through the use of Barber Asphalt Plants. The process was also introduced in Bombay, India after World War II.

Prior to and after WW II, recycling was embodied in the concept of stage construction, particularly the process of progressively improving the low-type roads. This method of reusing and upgrading existing pavement structures is a gradual strengthening process, which is really a recycling process. According to the Asphalt Institute [15]:

> "The first year the old pavement surface is bladed, an inch or two of new aggregate added and an asphalt treatment of 1/4 to 1/2 gallon per square yard is applied. The following year, a second aggregate and asphalt treatment is applied. The third year, definite weak areas should be located and strengthened with patch or aggregate base material. The fourth year should find a surface which can be used as a base or as a maintained surface."

The creation of the Interstate Highway System in 1956 shifted emphasis from maintenance and the rehabilitation of existing pavements, which included recycling, to construction of new pavements by most highway agencies. It has only been with the rapid rise in crude oil prices and the associated asphalt price increases, as well as the termination of new Interstate Highway construction, that recycling once again has surfaced as a viable rehabilitation method. Roads are fast approaching the point where corrective actions must be taken or the total system will suffer irreversible damage. Highway agencies are once again turning to recycling as a responsive, rehabilitation tool.

The Federal Highway Administration, USDOT, initiated Demonstration Project No. 39, "Recycling Asphalt Pavements," in June of 1976 "to promote and encourage the adoption of available recycling techniques."

Recycling has grown from 5000 tons per year in 1974 to, depending on the source of information, between 2 to 6 million tons by 1978. Douglas Bernard, Chief of the Construction and Maintenance Group, FHWA, estimates that by 1980, this country should be recycling close to 50 million tons per year [192]. Later in the decade, Bernard estimates that nearly 1/3 of the 300 to 400 million tons per year of asphalt paving will be recycled asphalt paving.

1.6 Classification of Recycling Methods

Today, a wide variety of methods exists by which asphalt pavements can be recycled. These methods vary according to the type of equipment used, the depth to which the operation is accomplished, the physical location of where the work takes place, and whether heat is used in the mixing process.

The Asphalt Institute and the National Asphalt Pavement Association have agreed on a general definition of recycling and the forms that it may

take [18,136]. Their joint definition defines recycling as;

> "The reuse, usually after some processing, of a material that has already served its first-intended purpose."

The Asphalt Institute and NAPA classify recycling into the following major divisions:

1. Hotmix Recycling: One of several methods where the major portion of the existing pavement structure, including in some cases, the underlying untreated base material, is removed, sized and mixed hot with added asphalt cement at a central plant. The process may also include the addition of new aggregate and/or a softening agent. The finished product is a hotmix asphalt base, binder or surface course.

2. Coldmix Recycling: One of several methods where the entire existing pavement structure, including in some cases the underlying base material, is processed in-place or removed and processed at a central plant. The materials are mixed cold and can be reused as an aggregate base, or asphalt and/or other materials can be added during mixing to provide a higher strength base. This process requires that an asphalt surface course be used.

3. Surface Recycling: One of several methods where the surface of an existing asphalt pavement is planed, milled or heated in place. In the latter case, the pavement may be scarified, remixed, relaid and rolled. Additionally, asphalts, softening agents, minimal amounts of new asphalt hotmix, aggregates or combinations of these may be added to obtain desirable mixture and surface characteristics. The finished product may be used as the final surface or may, in some instances, be overlaid with an asphalt surface course.

Another method of classifying recycling operations uses the physical place where the recycling takes place as the differentiating factor. Epps, et al. [18,65] and NCHRP Synthesis Panel Members [18] define the major divisions of recycling as:

1. Surface Recycling: Removal of the surface of a pavement to a depth of less than 1 inch by heater-planer, heater-scarifier, hot-planing or cold-planing devices. This operation is a continuous single pass, multistep process, which may involve the use of new materials including aggregates, modifiers or mixtures.

2. In-Place Surface and Base Recycling: In-place pulverization to a depth greater than 1 inch followed by reshaping and compaction. This operation may be performed with or without the addition of a modifier.

3. Central Plant Recycling: Scarification of the pavement materials, removal of the pavement from the roadway after or prior to pulverization, processing of material with or without the addition of a modifier, followed by laydown and compaction to desired grade. This operation may involve the addition of heat, depending upon the type of material recycled and modifier used.

Both sets of definitions are essentially the same, with hot mix recycling being almost synonymous with central plant recycling, and cold mix recycling being the same as in-place surface and base recycling. The latter set of definitions by Epps, et al. - Surface, Central Plant, and In-Place - will be used throughout the rest of this work.

CHAPTER TWO

RECYCLING GUIDELINES

Many different solutions are available to the pavement engineer who is charged with the responsibility of rehabilitating or reconstructing asphalt pavements. Depending on the type and magnitude of the pavement deficiency, a number of conventional maintenance and rehabilitation alternatives may be considered. Several recycling methods may also be considered as possible alternative solutions to return the deficient pavement to an acceptable level of service. However, unlike conventional methods which are generally well-known and widely practiced, recycling methods are virtually unknown and have only been sporadically used. Thus, even though the pavement engineer may be interested in the use of recycling as a corrective measure, the selection and application of an appropriate recycling method is uncertain and difficult.

One of the major problems facing the engineer who is considering the use of recycling as a pavement rehabilitation or reconstruction technique, is the problem of determining whether a pavement is a candidate for recycling. Furthermore, if it is determined that the pavement can be recycled, the engineer is faced with the problem of selecting one of the various recycling methods as an appropriate technique for that particular pavement. Previously, much of the decision making regarding the applicability of recycling methods was accomplished without any formal evaluation process. Many of the early recycling jobs were either arbitrarily selected as recy-

cling jobs, or were subjectively chosen (based on experience and intuition) to demonstrate a particular recycling method. This selection process resulted in a number of projects that were less than an unqualified success.

The purpose of the recycling guidelines is to establish a formal evaluation and investigation procedure to identify possible recycling candidates. The recycling guidelines will provide a rational method to evaluate the existing pavement, to determine the rehabilitation needs and to determine if recycling is an appropriate rehabilitation solution. As part of the recycling guidelines, a field evaluation and testing program is used to investigate and describe the condition of the existing pavement structure. A laboratory testing program is used to characterize the existing pavement materials and compare the current condition of the materials with the condition of the materials when the pavement was originally constructed. Through this process, the probable cause of failure can be determined and appropriate rehabilitation alternatives (conventional, as well as recycling) can be proposed. A recycled mix design is developed that incorporates the findings of the laboratory study. The final step in the recycling guidelines is the design of the recycled pavement structure. A flow chart illustrating the activities that comprise the recycling guidelines is illustrated in Figure 2-1.

2.1 Pavement Investigation and Characterization

A complex problem that must be solved when upgrading a pavement system is the determination of whether it is possible to continue to maintain an existing pavement or whether rehabilitation or reconstruction is required. Furthermore, if rehabilitation is indicated, the incorporation of the existing pavement must be determined.

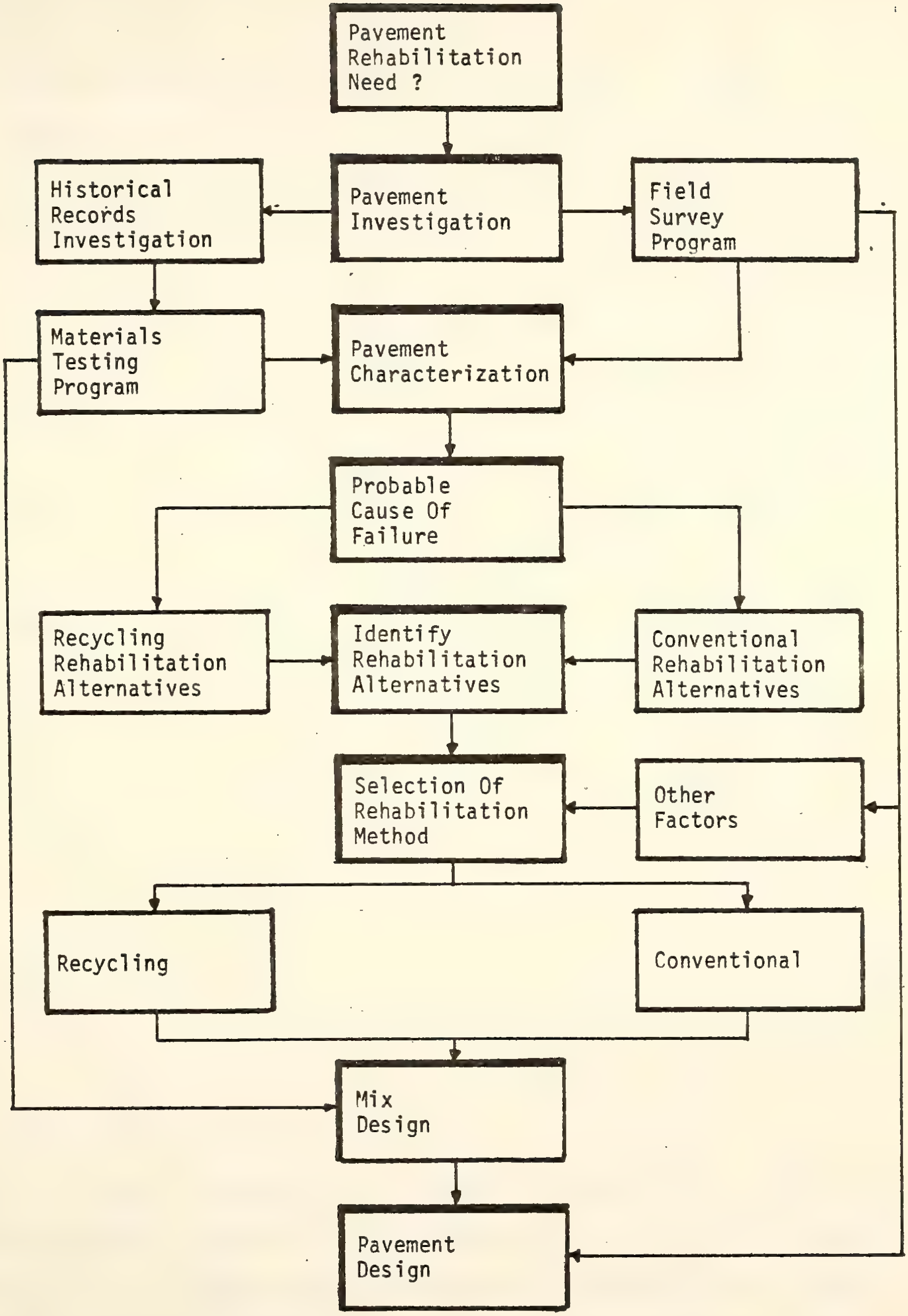


Figure 2-1 Recycling Guidelines

Pavement rehabilitation can be defined as "a method or process by which the pavement can be restored to a satisfactory condition" [163]. However, before a solution can be proposed, the condition of the existing pavement must be defined. All pavement deficiencies can be classified into one or two major categories: structural failures; and functional failures [241]. Structural failure is defined as a breakdown in the pavement system such that the pavement is incapable of adequately sustaining the load placed upon the surface of the pavement. Functional failure, which may or may not be accompanied by structural failure, is defined as the inability of the pavement system to carry out its intended function for the highway user. Highways are designed to provide the user with a safe, comfortable, convenient and economical method of transporting goods and services. Any time the pavement fails to perform its intended functions, it provides the user with a less than desirable level of service. Obviously, the degree of distress, whether functional or structural, is extremely variable. Thus, it is left to the pavement engineer to determine if the severity of the failure dictates corrective action and, if indicated, what corrective action should be taken.

2.1.1 Field Survey Program

The Field Survey Program, outlined in Figure 2-2, provides a means to formally evaluate a pavement and determine its rehabilitation needs. The first step in the process is the determination of the functional classification of the road. Functional classification is a method by which roads and streets with similar functions, purposes and importance in the total highway network can be grouped together. There are many different classification systems in use today. One such system classifies highways into the following groups [24]:

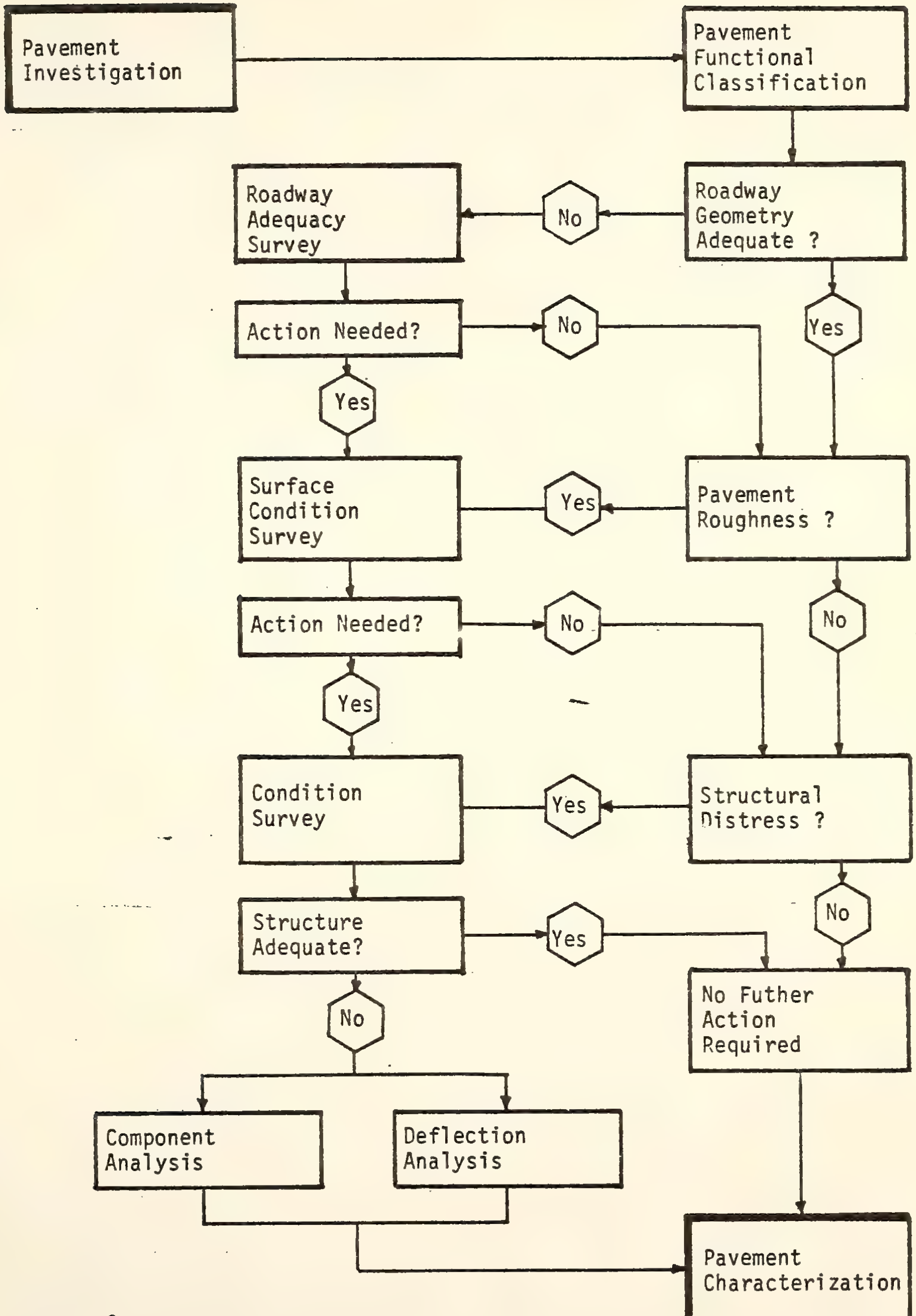


Figure 2-2 Field Survey Program

1. Freeways
2. Arterials
3. Collectors
4. Land Service or Local
5. Scenic

These groups may be further subdivided according to whether the pavement is located in a rural or urban environment. Obviously, each of these groups has different requirements as to the level of service the pavement must provide to the highway user.

2.1.1.1 Pavement Geometry Survey. Following highway classification, the next step in the Field Survey Program is the determination of the highway's geometrical adequacy. Many older roads were designed for low traffic volumes and slow speeds [19]. Increased traffic and improved level of service demanded by users may require that the geometric design of the road be changed. Thus, the geometric adequacy of the pavement should be evaluated and, if found deficient, corrective actions can be included as part of the rehabilitation process. Items that should be checked are listed in the worksheet illustrated in Figure 2-3.

Following the survey, a rational decision can be made as to the need for upgrading or correcting the roadway geometry. If no corrective actions are indicated, the pavement surface should be surveyed for rideability. If the pavement rides roughly, a surface condition survey should be conducted to determine the magnitude of the distress.

2.1.1.2 Surface Condition Survey. The surface condition survey provides valuable and necessary information regarding the adequacy of the existing pavement surface in fulfilling its task with respect to current service requirements [19].

A distinction should be made between a condition survey and an evaluation survey [241]. The condition survey is a method that determines pave-

Road ______________________ Functional Classification ______________

Contract Number ______________ Design Traffic ______________________

	Measurement or Condition	Comments
Travel Lane		
Lane Width		
Number of Lanes		
Climbing Lanes		
Acceleration Lanes		
Deceleration, Turning, Storage Lanes		
Shoulders		
Width		
Median (Divided Highways)		
Alignment		
Horizontal		
Curvature		
Line of Sight		
Right of Way		
Vertical		
Curvature		
Line of Sight		
Grade		
Cross-Section		
Crown or Slope (including shoulders)		
Transistions-Edges		
-Intersections		
Drainage Ditches		
Appurtenances		
Curbs		
Gutters & Drains		
Utility Structures		
Overhead Clearances		
Safety Structures		

Figure 2-3 Roadway Geometry Survey

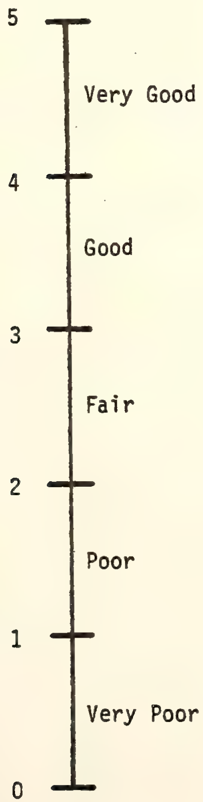
ment condition at a given point in time. Generally, no attempt is made to determine the cause of the conditions encountered. Thus, the condition survey is qualitative in nature, usually relying on the subjective rating of an individual rater, disregarding the actual character of the pavement. On the other hand, the evaluation survey determines the need for a structural adequacy evaluation and determines the cause(s) of distress. The surface condition survey is part of this process. However, the evaluation survey is more inclusive, considering such items as pavement type, thickness, material quality and traffic conditions.

The methods used to survey and rate the surface condition of a pavement structure employ the present serviceability concept. Present serviceability is the ability of a specified section of pavement to provide, in the opinion of the user, a smooth and comfortable ride at a particular time [19]. The two methods commonly used to measure surface condition are Present Serviceability Rating (PSR) and Present Serviceability Index (PSI). PSR is determined by a group of raters who ride over a pavement section, observe its rideability and record their opinions as to its ability to serve the traffic using the road at that moment. Each panel member fills out a card (see Figure 2-4) rating the pavement on a scale of 0 to 5, with the higher numbers indicating a satisfactory condition and the lower numbers usually indicating that the level of service is unsatisfactory and corrective actions may be needed. The average (or mean rating) of the panel is defined as the PSR.

The Present Serviceability Index is based upon the use of statistical regression analysis to correlate the users' opinions of present serviceability with actual measurements of road roughness, cracking, patching and rutting. For flexible pavements, the AASHTO road test equation for PSI is [241]:

Section Number	Highway Number

Vehicle	Date a.m. p.m.	Rater



Influence of behavior elements on present serviceability rating.	No Influence	Minor Influence	Appreciable Influence	Pronounced Influence
Longitudinal Distortion				
Transverse Distortion				
Cracking				
Faulting				
Surface Deterioration				

Acceptable	
Yes	
No	
Doubtful	

Figure 2-4 Present Serviceability Rating (after Yoder & Witczak - 241)

$$PSI = 5.03 - 1.9 \log(1+SV) - 0.01(C+P)^{1/2} - 1.38RD^2 \qquad (2.1)$$

where:
PSI = Present Serviceability Index
SV = Slope variance (measured by a slope profilometer)
C = Lineal feet of major cracking per 1000 sf area
P = Bituminous patching in sf per 1000 sf area
RD = Mean rut depth in inches (both wheel tracks), measured with a 4 foot straight edge

Because the determination of PSI, using the AASHTO roadtest equation, involves a considerable amount of time-consuming measurements and because the primary factor influencing serviceability is longitudinal roughness, several mechanical or electrical systems have been developed to accurately and rapidly measure pavement roughness. Among the devices developed and commonly used are:

1. Roughometer - a device, which when towed over a pavement surface, is assumed to stay in a relatively fixed plane due to its own inertia. Changes in elevation are measured by a floating wheel. The statistic obtained is inches per mile and may be correlated directly with PSI.
2. Towed longitudinal profile measuring device - a device which can plot variations in slope of pavement surface with respect to the line of the vehicle travel. The statistic derived is slope variance and may be correlated with PSI.
3. Road Meter - commonly referred to as the PCA Road meter. It is a device, mounted integrally on a test vehicle, that measures the number and magnitude of deviations of the rear axle from the vehicle's frame. Deviations in 1/8 inch increments, with reference to the standing position of the automobile, are measured and recorded. The statistics obtained is inches squared per mile and may be used to calculate slope variance and PSI.

The PCA Roadmeter readings can be used to calculate the slope variance (SV) used in equation 5.1. The roadmeter statistic $\sum(D^2)$ is calculated using the following equation:

$$\sum(D^2) = \frac{1a + 4b + 9c + 16d + \ldots}{64} \qquad (2.2)$$

where: a = number of deviation readings equal to 1/8 inch
b = number of deviation readings equal to 2/8 inch
c = number of deviation readings equal to 3/8 inch
d = number of deviation readings equal to 4/8 inch
etc.

$\sum(D^2)$ may be used as a pavement roughness indicator itself or may be used to calculate the slope variance using the following equations.

$$SV = 0.68\sum(D^2) + .8 \qquad (2.3)$$

The slope variance is used to calculate PSI. See equation 2.1.

The roughometer readings, in inches per mile, can be used to calculate PSI using the following equation:

$$PSI = 5.00 - 0.015R - 0.140 \log R \qquad (2.4)$$

where: R = roughometer value, in inches per mile.

PSR or PSI is used to indicate relative pavement surface condition and permits rating of pavements on a common basis. A serviceability rating of a particular magnitude should indicate the same surface condition regardless of the pavement location. PSR/PSI can be used to determine whether to proceed with or postpone a more detailed investigation. Depending on the functional classification of the road being surveyed, a low PSR/PSI value indicates poor pavement condition and suggests that a more detailed examination of the surface is required. PSR/PSI ratings of 2.5 to 2.0 have generally been accepted as the minimal value, below which further evaluation

and corrective measures may be necessary [19,241]. Thus, as part of the surface condition survey, a minimum PSR/PSI value should be selected as a decision criterion. Any pavement with a rating below this value should be further evaluated.

A surface measurement that is not part of the surface condition survey is frictional skid resistance. Skid resistance, because it is directly related to highway safety, is also an important surface condition attribute. Due to many different factors (materials, traffic and environment), pavement surfaces will lose their skid resistant properties with age and use. It is generally recognized that when skid resistance falls below a minimum value, corrective action is needed. The statistic used to measure skid resistance is the skid number - SN.

Skid tests are normally conducted utilizing a locked-wheel trailer, conforming to ASTM standard designation E 274. The test speed has been standardized at 40 mph. A minimum skid number should be selected as the value below which corrective action should be taken to restore pavement skid resistance. Many agencies have selected a skid number of 35 (40 mph) as the minimum value.

2.1.1.3 Condition Survey. If the surface condition survey indicates the need for corrective action(s) or if the existence of obvious structural defects is noted, a thorough investigation of the pavement distress should be conducted. The pavement should be carefully surveyed and evaluated. A detailed record should be made of each type of distress encountered, as well as the severity of the distress and its location. This type of survey, a condition survey (not to be confused with a surface condition survey), seeks to establish the cause(s) of the defect(s) [19,80].

There are many types of defects or forms of distress that may develop in a flexible pavement. These may be classified into four categories [17,124,163]:

1. Cracking
2. Distortion
3. Disintegration
4. Skid Hazard

Distress manifestations (problems) associated with flexible pavements can be assigned to one of the four distress modes listed above. (See Figure 2-5.) Accurate identification of the distress manifestation is important in determining the mechanism producing the defect. Listed in Tables 2-1, 2-2, 2-3 and 2-4 are the major types of asphalt pavement distress and a brief description of the distress manifestation.

There is no single condition survey that is universally used. There are nearly as many methods to accomplish the survey as there are agencies conducting condition surveys [80]. Although the reporting format varies considerably, in general, the condition survey allows the rater to note the types of distress encountered, the severity of the distress, the degree or density of the distress and the location of the distress. Examples of condition survey forms are illustrated in Figures 2-6 and 2-7. The simple form illustrated in Figure 2-6 allows the rater to identify the existence of and subjectively evaluate the density and severity of pavement distress manifestations. The rating form illustrated in Figure 2-7 is more detailed and provides guidance in defining distress manifestation severity and density.

If the condition survey indicates that the structural adequacy of the pavement is questionable or if the survey finds defects that indicate that a structural problem might exist, the strength of the pavement should be evaluated. This evaluation may be accomplished by structural component

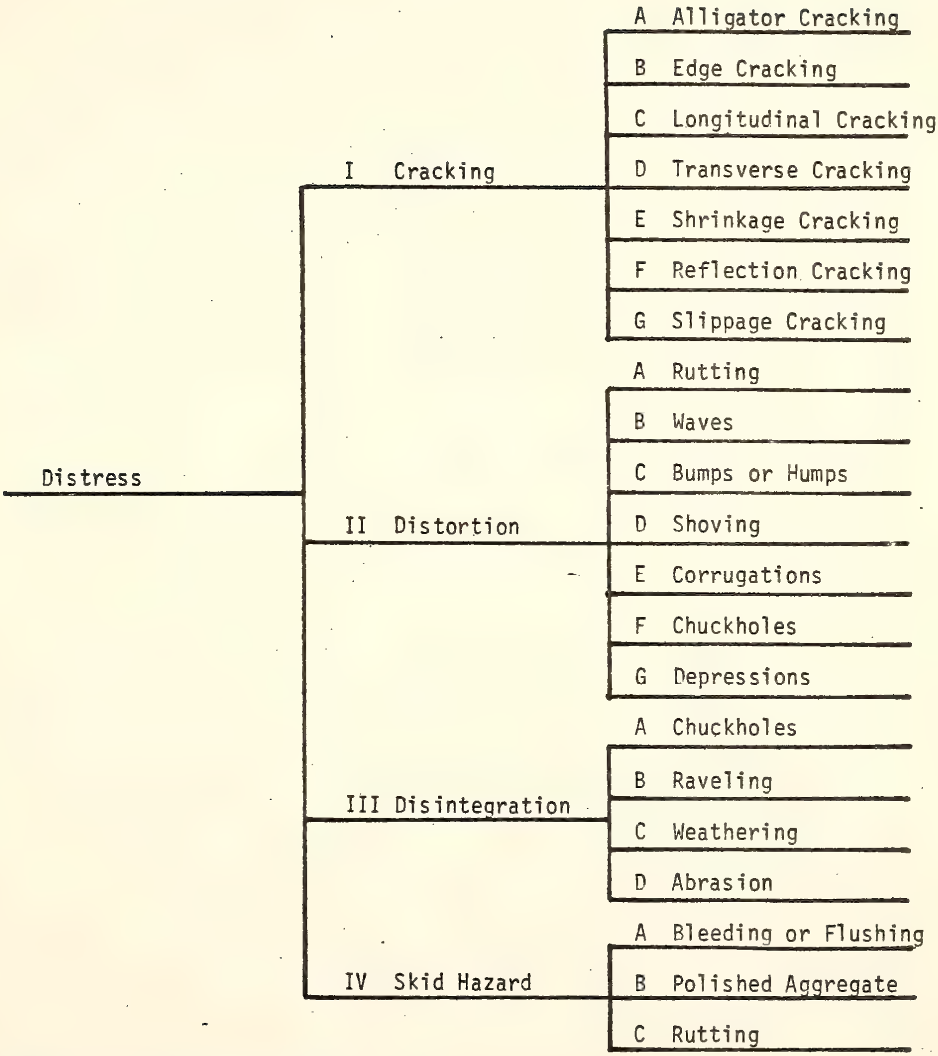


Figure 2-5 Distress Classification

Table 2-1 Cracking

Type of Distress (Manifestation)	Definition or Description of Distress (17,221,241)
A Alligator Cracks	Interconnected or interlaced small polygon cracks
B Edge Cracks	Longitudinal cracks parallel to and near the edge of the pavement (within 1 or 2 feet of the pavement edge)
C Longitudinal Cracks	Cracks parallel to the pavement centerline
D Transverse Cracks	Cracks at right angle to the pavement centerline
E Shrinkage Cracks	Random interconnected cracks
F Relection Cracks	Reappearance of rigid pavement cracks in flexible pavement overlay
G Slippage Cracks	Half-moon or crescent-shaped cracks pointing in the direction of travel

Table 2-2 Distortion

Type of Distress (Manifestation)	Definition or Description of Distress (17,221,241)
A Rutting or Channelization	Longitudinal depressions, greater than 20 inches in length, located in the wheel paths
B Waves	Longitudinal or transverse undulations with crest-valley distances greater than 2 feet
C Shoving	Displacement or bulging in the direction of loading
D Bumps or Humps	Localized upward displacement
E Corrugations	Transverse undulations at right angles to the surface with crest-valley distances of less than 2 feet
F Chuckholes or Potholes	Bowl-shaped holes, small localized failure
G Depressions	Localized area of lower pavement elevation

Table 2-3 Disintegration

Type of Distress (Manifestation)	Definition or Description of Distress (17,221,241)
A Chuckholes or Potholes	Bowl-shaped hole, small localized failure
B Raveling	Progressive disintegration, from the surface down, by displacement of aggregate particles
C Weathering	Gradual disintegration of wearing surface increasing texture, exposing more aggregate
D Abrasion	Scuffing of wearing course

Table 2-4 Skid Hazard

Type of Distress (Manifestation)	Definition or Description of Distress (17,221,241)
A Bleeding or Flushing	Free asphalt on surface, especially in wheel paths
B Polished Aggregate	Smoothing or polishing or pavement surface aggregate
C Rutting or Channelization	Longitudinal depressions, greater than 20 inches in length, located in the wheel paths that collect water

analysis or pavement deflection analysis. Structural component analysis calculates pavement strength using the material properties and thickness of the existing base and asphalt-bound layers. Pavement deflection analysis calculates pavement strength by measuring the deflection of a pavement subjected to a standardized load.

2.1.1.4 Structural Component Analysis. The process of evaluating the structural strength of an existing pavement by component analysis is similar to the process of designing a new pavement [19]. However, the existing pavement must be evaluated on the basis of the quality and the thickness of its components, rather than new material properties and specified layer thickness.

The initial step in the component analysis process is the determination of the existing pavement's subgrade strength properties. When original design records are available, the subgrade strength used in the design process may be used. However, a limited amount of testing should be conducted to substantiate the strength assumed. This precautionary testing will indicate if any changes in soil conditions have occurred during the service life of the existing pavement.

If the original design data is not available, sufficient soil samples (minimum of three recommended) should be obtained from each class of soil encountered throughout the project. Soil classes can be determined from soil survey maps or from actual soil survey data. The strength properties for each subgrade sample should be determined using either the CBR method (ASTM Desination D-1883) or the Resistance-R value method (ASTM Designation D-2844).

The Design Subgrade Strength (DSS) value should be calculated using the subgrade strength properties of each soil sample. The Design Subgrade

Highway ______________________ Location ______________________

Length ______________________ Width ______________________

Pavement Type ______________________ Date ______________________

Pavement Distress Manifestation	Evaluation		
	Severity	Density	Other Comments
Cracking			
Alligator			
Longitudinal-wheel track			
-midlane			
-centerline			
-edge			
Transverse			
Shrinkage			
Reflection			
Slippage			
Distortion			
Rutting			
Waves			
Bumps or Humps			
Shoving			
Corrugations			
Chuckholes			
Depressions			
Disintegration			
Chuckholes			
Raveling			
Weathering			
Skid Hazard			
Bleeding			
Polished Aggregate			
Rutting			

Figure 2-6 Simple Condition Survey

Highway ______________ Length ______________ Width ______________
Location ______________ Date of Survey ______________
Pavement Type ______________

Pavement Distress Manifestation			Distress Severity			Distress Density			Distress Characteristics				
			Slight	Moderate	Severe	Few 0-20 %	Frequent 20-80 %	Throughout 80-100 %	Reflection Cracking	Pavmt. Edge: Progressive >12 in.	Pavmt. Edge: Non-progressive <12 in.	Trans. Crack Spacing ft.	Alligator Block Size in.
Cracking	Longitudinal Wheel	Single											
		Multiple											
		Alligator											
	Midlane	Single											
		Multiple											
	Center Line	Single											
		Multiple											
		Alligator											
	Meander	Single											
		Multiple											
	Pavement Edge	Single											
		Multiple											
		Alligator											
	Transverse	Partial											
		Half											
		Full											
		Multiple											
		Alligator											
	Random												
	Slippage												
Distortion	Rutting												
	Waves												
	Bumps or Humps												
	Shoving												
	Corrugations												
Disintegration	Chuckholes												
	Raveling												
	Weathering												
Skid Hazard	Bleeding												
	Polishing												
	Rutting												

Figure 2-7 Detailed Condition Survey (after Haas & Hudson - 80)

Strength is defined as the strength that approximately 85% of all test values (in a specific section) are equal to or greater than.

The next step in the component analysis process is the evaluation of the pavement components. Each pavement layer must be converted into an Effective Thickness (T_e). The Effective Thickness of an existing pavement is that thickness that would be required if the existing pavement were converted to an equivalent full depth asphalt concrete of the same load carrying characteristics. Conversion factors used to calculate T_e are listed in Table 2-5 by classification of pavement layer and material characteristics. The use of this table requires that subbase, base and asphalt layers be properly sampled and characterized to determine material properties and actual layer thicknesses.

The Effective Thickness of each layer is calculated by multiplying the actual layer thickness by the appropriate conversion factor. T_e for the total pavement structure is the sum of T_e for all layers.

Once the effective pavement thickness has been calculated, the next step in the component analysis process is traffic analysis, which includes volume, composition and axle weights. When available, the latest traffic survey statistics are suitable, if they accurately reflect the current traffic conditions. However, if the information is out of date or does not reflect conditions as they now exist, a new traffic survey should be conducted. The traffic survey information is used to calculate the Design Traffic Number (DTN). The Design Traffic Number is the average daily number of equivalent 18,000 pound, single axle load applications expected on the Design Lane during the Design Period. The Design Lane is the lane on which the greatest number of equivalent 18,000 pound single axle loads is expected. The Design Period is the number of years until major reconstruction is

Table 2-5 Conversion Factors for Calculating Effective Thickness (19)

Classification of Material	Description of Material	Conversion Factors
I	Native subgrade in all cases	0.0
II	Improved subgrade-Predominantly granular materials, may contain some silt and clay, but have a PI of 10 or less (improved subgrade= any course or courses of improved material between the native subgrade soil and the pavement structure)	0.0-0.2
	Lime modified subgrade constructed from high plasticity soils-PI greater than 10. (Lime modified subgrade=A prepared and mechanically compacted unhardened or semihardened intimate mixture of lime, water and soil below the pavement system)	0.0-0.2
III	Granular subbase or base-Reasonably well-graded, hard aggregates with some plastic fines. and CBR not less than 20. Use upper range if PI is 6 or less; lower range if PI is more than 6.	0.2-0.3
	Cement modified subbases and bases constructed from low plasticity soils-PI of 10 or less. (Cement modified subbase or base=An unhardened or semihardened intimate mixture of pulverized soil,portland cement, and water used as a layer in the pavement system to reinforce and protect the subgrade or subbase.)	0.2-0.3
IV	Granular base-Nonplastic granular material complying with established standards for high quality aggregate base. Use upper part of range.	0.3-0.5
	Asphalt surface mixtures having large well defined crack patterns, spalling along the cracks, exhibit appreciable deformation in the wheel paths showing some evidence of instability.	0.3-0.5
	Portland cement concrete pavement that has been broken into small pieces, 2 feet or less in maximum dimension, prior to overlay construction. Use upper part of range when subbase is present; lower part of range when slab is on subgrade.	0.3-0.5

Table 2-5 (continued) Conversion Factors for Calcualting Effective Thickness (19)

Classification of Material	Description of Material	Conversion Factors
IV	Soil-cement bases that have developed extensive pattern cracking, as shown by reflected surface cracks, may exhibit pumping and pavement shows minor evidence of instability.	0.3-0.5
V	Asphalt surfaces and underlying asphalt bases that exhibit appreciable cracking and crack patterns, but little or no spalling along the cracks and while exhibiting some wheel path deformations, remain essentially stable.	0.5-0.7
	Appreciably cracked and faulted portland cement concrete pavement that cannot be effectively undersealed. Slab fragments ranging in size from 1 to 4 square yards, well seated on subgrade.	0.5-0.7
	Soil-cement bases that exhibit little cracking, as shown by reflected surface crack patterns, and that are under stable surfaces.	0.5-0.7
VI	Asphalt concrete surfaces that exhibit some fine cracking, small intermittent cracking patterns and slight deformation in the wheel paths but remain stable.	0.7-0.9
	Liquid asphalt mixtures that are stable, generally uncracked, show no bleeding and exhibit little deformation in the wheel paths.	0.7-0.9
	Asphalt treated base, other than asphalt concrete	0.7-0.9
	Portland cement concrete pavement that is stable and undersealed, pieces no smaller than 1 yard.	0.7-0.9
VII	Asphalt concrete, including asphalt concrete base generally uncracked and with little deformation in the wheel paths.	0.9-1.0
	Portland cement concrete pavement that is stable undersealed and generally uncracked.	0.9-1.0
	Portland cement concrete base, under asphalt surface that is stable, non-pumping and exhibits little reflected surface cracking.	0.9-1.0

anticipated.

A simplified approach [19] that can be used to calculate the Design Traffic Number is listed below:

1. Using the traffic survey statistics, estimate the average daily number of vehicles, in both directions, expected during the first year after the road is reconstructed. This is the Initial Daily Traffic - IDT.

2. Estimate the average daily number of heavy trucks expected on the design lane (one direction only).

$$\text{Number of Heavy Trucks} = \text{IDT} \times A/100 \times B/100 \qquad (2.5)$$

where: A = percent of heavy trucks in the design lane

B = percent of heavy trucks in traffic stream

Note: See Tables 2-6 and 2-7 if data unknown.

3. Estimate the average gross weight of the heavy trucks. Information may be obtained from weight studies or estimated using Table 2-7.

4. Determine the legal, single axle load limit established by state or local statutes.

5. Determine the Initial Traffic Number (ITN) by use of the traffic analysis chart illustrated in Figure 2-8. Enter the chart with the average gross of heavy trucks on line D. On line C locate the number of heavy trucks (daily average on design lane), connect the points on lines C and D and extend the line to intersect line B. The point of intersection is the pivot point. On line E, locate the single axle load limit. Connect the point on line E with the pivot point on line B and extend the line to intersect line A. The point of intersection on line A is the Initial Traffic Number

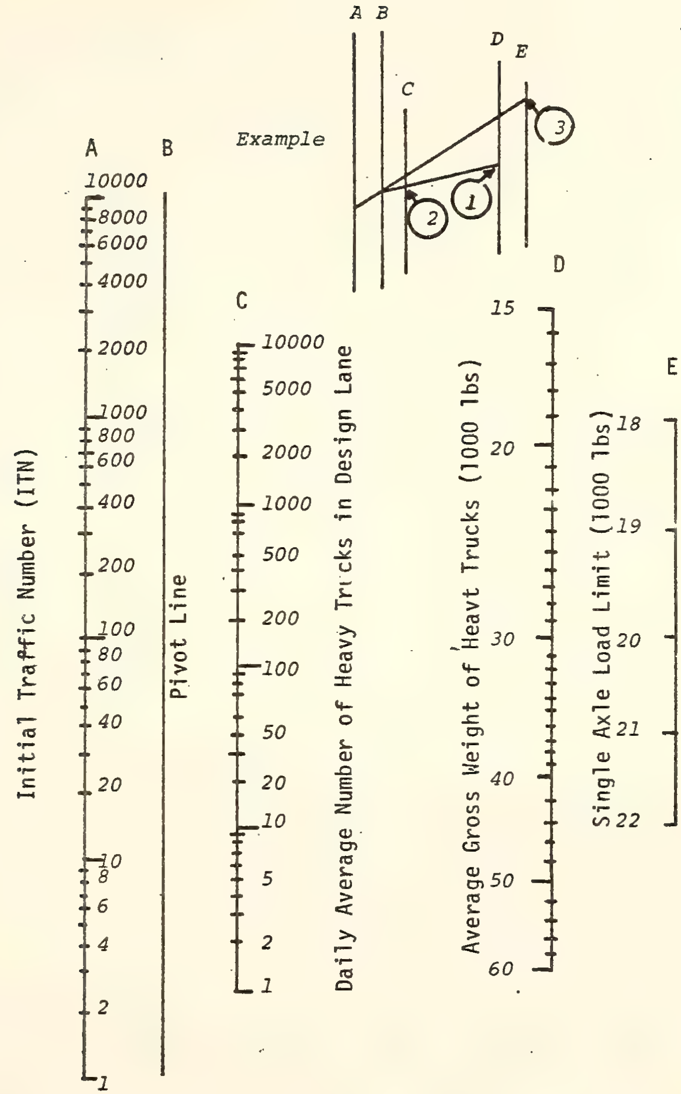


Figure 2-8 Traffic Analysis Chart (Asphalt Institute - 19)

(ITN).

6. If the ITN is 10 or less, a correction for the daily volume of automobiles and light trucks in the design lane is needed. Use the chart illustrated in Figure 2-9. Enter the chart (abscissa) with the daily volume of automobiles and light trucks. Move vertically to the curve representing the ITN, based on heavy trucks, determined in step number 5. Moving horizontally, read the corrected ITN off the graph ordinate.

7. Establish the design period - n (number of years until major resurfacing or reconstruction is anticipated) and estimate the annual rate of traffic growth - r. Calculate the Initial Traffic Number Adjustment Factor (ITNAF) using the following equations:

$$ITNAF = \frac{(1 + r)^n - 1}{20r} \tag{2.6}$$

where: r = annual growth rate
n = design period, years
note: Design charts illustrated in Figures 2-10 and 2-11 are based on a 20 year design period. The use of equation 2.6 converts the average daily number of equivalent 18,000 pound single axle load applications during the design period to an equivalent number of 18,000 pound applications in a 20 year design period.

8. Determine the Design Traffic Number (DTN) by multiplying ITN (steps 5 and 6) by the Initial Traffic Number Adjustment Factor - ITNAF (step 7).

Using the Design Subgrade Strength (DSS), the Design Traffic Number (DTN) and Effective Thickness (T_e), the structural adequacy of the existing pavement can be evaluated. The procedure can be used to determine either the need for structural rehabilitation or to estimate the time before struc-

Table 2-6 Percentage of Truck Traffic in Design Lane (Asphalt Institute)

Number of Traffic Lanes (Two Directions)	Percentage of Trucks in Design Lane
2	50
4	45 (35-48)*
6 or more	40 (25-48)*

* Probable Range

Table 2-7 Estimated No. Trucks and Ave. Gross Weight (Asphalt Institute)

Description of Highway or Street	Percent Heavy Trucks	Average Gross Weight (1000 pounds)
City Streets (local)	5 or less	15 - 25
Urban Highways		
Primary	5 - 15	20 - 30
Interstate	5 - 10	35 - 45
Local Rural Roads	15 or less	15 - 25
Interurban Highways		
Primary	5 - 20	30 - 40
Interstate	10 - 25	35 - 45

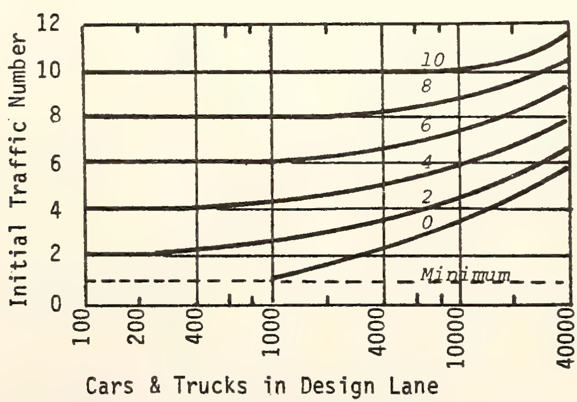


Figure 2-9 Initial Traffic Number Adjustment Chart (Asphalt Institute)

tural rehabilitating is required.

The design charts in Figures 2-10 and 2-11 are used to determine if the existing pavement is structurally adequate or if rehabilitation is needed. Connect the DTN on line C and the DSS on line B with a straight line and extend the line until it intersects line A. The value at which the extended line intersects line A is the total thickness of asphalt concrete (T_A) above the prepared subgrade that is required for traffic and load conditions. If T_A is less than T_e the pavement is structurally adequate at this time. However, if T_A is greater than T_e, some form of structural rehabilitation is indicated.

The average remaining pavement life until a structural upgrading is required can be determined if T_A is less than T_e. The design charts (Fig. 2-10 and 2-11) are entered with $T_A = T_e$ and Design Subgrade Strength. A line connecting these points and intersecting line C yields an Adjusted Design Traffic Number (ADTN). Dividing ADTN by the Initial Traffic Number yields the Initial Traffic Number Adjustment Factor (ITNAF).

$$ITNAF = \frac{ADTN}{ITN} \qquad (2.7)$$

Since:

$$ITNAF = \frac{(1 + r)^n - 1}{20\ r} \qquad (2.8)$$

n (the remaining useful life) can be calculated by the equation:

$$n = \frac{\log(20r \times ITNAF + 1)}{\log(1 + r)} \qquad (2.9)$$

Thus, n indicates the number of years remaining before the pavement should be structurally upgraded.

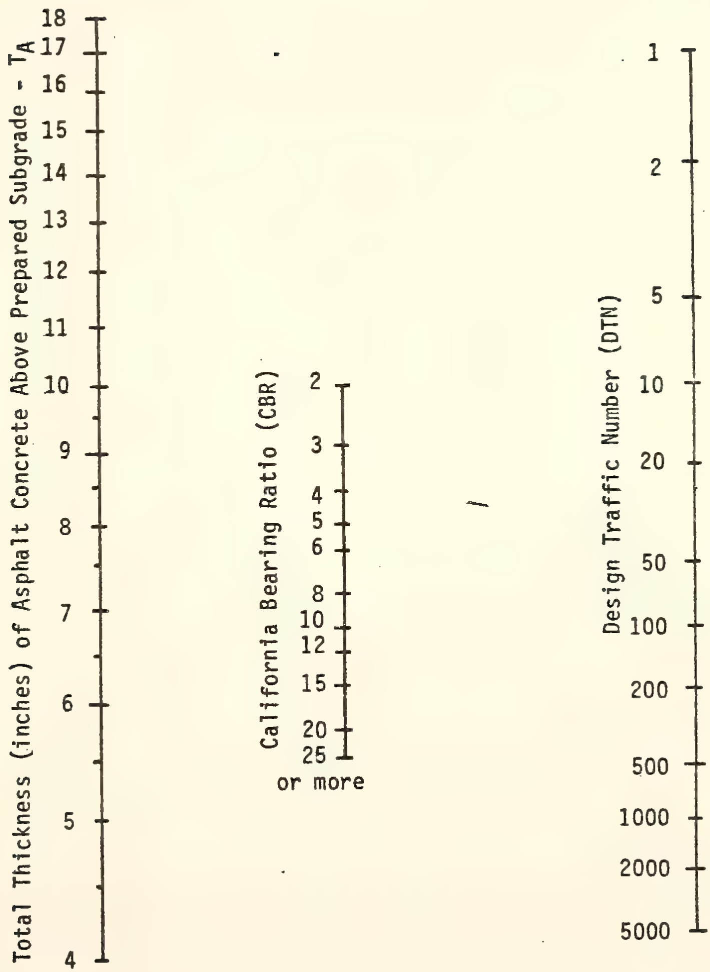


Figure 2-10 Thickness Requirements Using CBR (Asphalt Institute - 19)

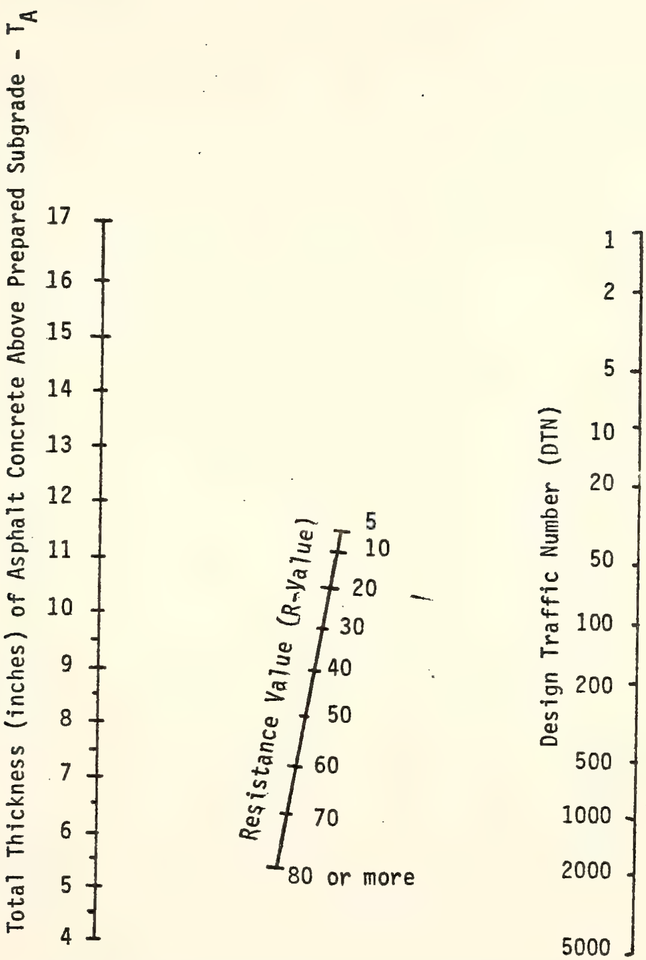


Figure 2-11 Thickness Requirements Using R-Value (Asphalt Institute-19)

2.1.1.5 Pavement Deflection Analysis. Pavement Deflection Analysis is the other evaluative technique that can be used to measure a pavement's structural adequacy. This non-destructive testing procedure relates the pavement's ability to withstand traffic loading to the magnitude of surface deflection that occurs as a result of a standarized load applied to the pavement surface. A considerable amount of research has been conducted to establish a correlation between wheel loads, pavement deflection, load repetitions and the structural adequacy of a pavement.

Many different methods can be used to evaluate pavement deflection [132]. However, two of the most common methods are the Benkleman Beam and the Dynaflect. The Benkleman Beam measures the response of a pavement to a single application of a slow moving or static load. The Dynaflect system measures pavement deflection due to a dynamic force generated by a sinusoidal vibrator.

The Benkleman Beam is a device that has a long (12 foot), narrow, levered beam that is slipped between the dual tires of a loaded truck [19,132]. The instrument has the capability to measure the total pavement deflection as the test truck is moved ahead. Total rebound deflection is the amount of vertical movement of the pavement surface that occurs when the load is removed from the surface, and is measured in mills (1/1000 inch). Deflection tests should be conducted 2 to 3 feet from the outside edge of the pavement and at randomly selected longitudinal points. Pavement surface temperature should be measured at least once per hour. A Representation Rebound Deflection (RRD) should be calculated for the pavement section. RRD is calculated by the following equation:

$$RRD = (\overline{X} + 2s)fc \tag{2.10}$$

where: $\overline{X}$ = arithmetic mean of individual rebound measurements
s = standard deviation of rebound measurements (if less than 10 measurements are taken per section, the standard deviation should be estimated)
f = temperature adjustment factor
c = critical period and adjustment factor

The temperature adjustment factor is determined from Figure 2-12. The mean pavement temperature is the average of the temperatures at the surface, middle and bottom of the total asphalt-bound portion of the pavement. Pavement temperature at varying depths can be estimated using Figure 2-13.

The critical period adjustment factor (CPAF) is used to relate pavement performance at the time of the test, to the pavement's performance at certain critical times of the year. If the test is conducted during the critical period, the CPAF is 1.0. If the test is conducted at periods other than the critical time, either an estimate, based on sound engineering judgment, or a previously computed value must be used. The CPAF is calculated by:

$$CPAF = \frac{\text{Critical Period Rebound Deflection}}{\text{Testing Period Rebound Deflection}} \tag{2.11}$$

Once the Representative Rebound Deflection is calculated, the structural adequacy of the pavement can be evaluated using the graph illustrated in Figure 2-14. Enter the graph with the DTN computed for present and future road conditions and determine the corresponding design rebound deflection. If the design rebound deflection is less than the Representative Rebound Deflection (calculated by formula 2.10), the pavement is structurally inadequate. If the design rebound deflection is greater than the Representative Rebound deflection, the pavement is structurally adequate and the remaining life can be approximated by letting the Representative Rebound Deflection equal the design rebound deflection. The chart in Figure 2-14 is entered

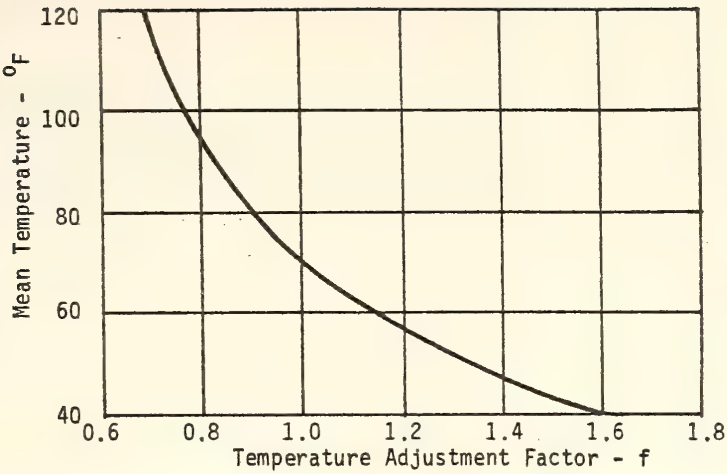


Figure 2-12 Temperature Adjustment Factor (Asphalt Institute - 19)

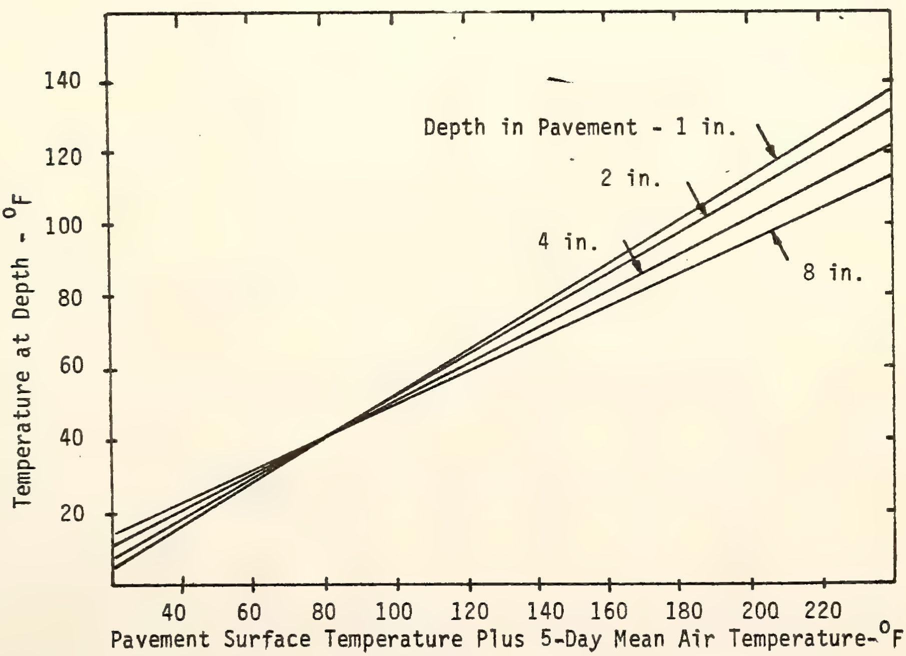


Figure 2-13 Predicted Pavement Temperatures (Asphalt Institute - 19)

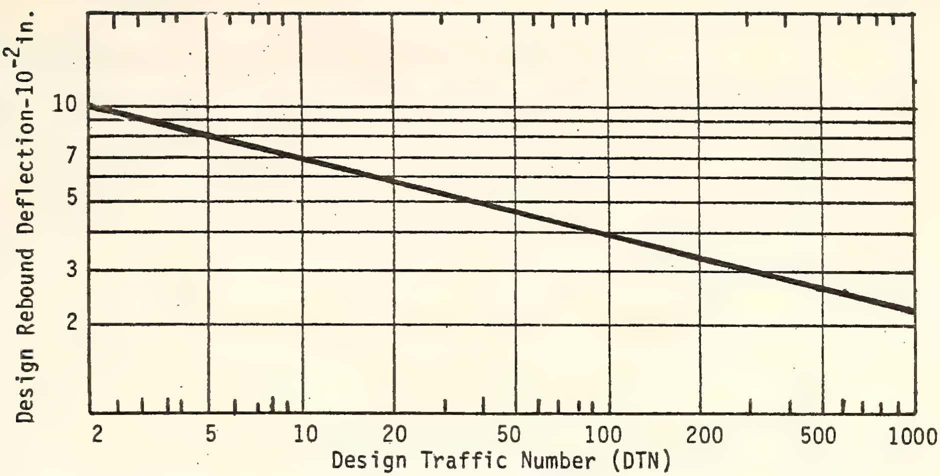


Figure 2-14 Design Rebound Deflection Chart (Asphalt Institute - 19)

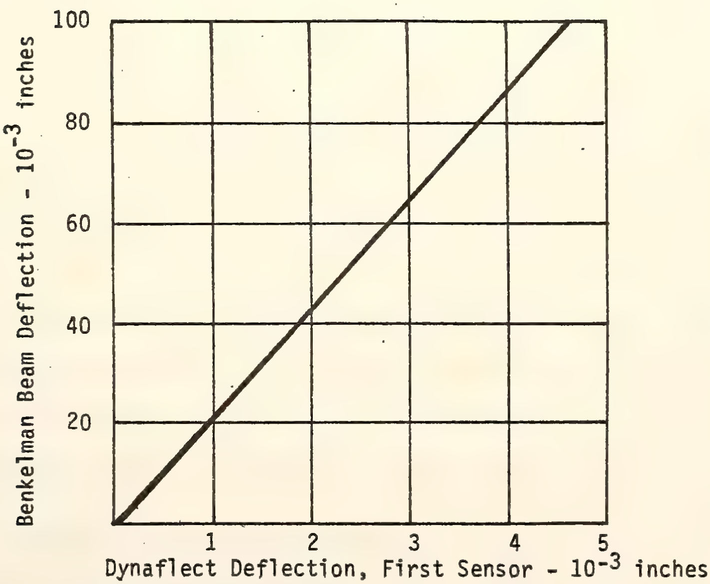


Figure 2-15 Relationship Benkelman Beam and Dynaflect Deflection (Asphalt Institute - 19)

with the RRD, and an Adjusted Design Traffic Number is read off the Design Traffic Number scale. The approximate number of years, n, before reconstruction is needed is computed by equations 2.7 and 2.9.

Another tool that can be used to measure pavement deflection is the Dynaflect system [19,132]. The system consists of a device that imparts a dynamic force of 1000 pounds to the pavement surface via a pair of small, steel loading wheels. The resulting pavement deflection, usually measured in mills, has been correlated with Benkleman Beam Deflections. To convert a Dynaflect deflection to an equivalent Benklemen Beam Rebound deflection, use the chart illustrated in Figure 2-15.

The equivalent Benklemen Rebound Deflections are treated as conventional rebound deflections and are used to calculate a Representative Rebound Deflection using equation 2.10. From this point on, the evaluation of structural adequacy is the same as the Benkleman beam.

This completes the Field Survey Program. Deficiencies and rehabilitation needs of the existing pavement have been identified. Depending upon the classification and type of highway surveyed, substandard conditions that should be corrected are identified. Geometric deficiencies, as well as surface conditions that result in a low level of serviceability are identified. Defects or distress mechanisms that result in unsatisfactory pavement performance are identified and classified. Finally, the structural adequacy of the existing pavement is evaluated. All of this information will be used to select a method than can be used to rehabilitate the existing pavement.

2.1.2 Historical Records Investigation and Materials Testing Program

The evaluation program outlined in Figure 2-16 provides a means to characterize the existing pavement structure, particularly the material components of the pavement structure. Historical records maintained on the ex-

isting pavement are studied to determine what should exist in the field. A laboratory testing program analyzes field samples and determines what actually exists in the field. The information obtained from this program, when combined with the results of the field survey program, should fully characterize the existing pavement and allow the probable cause of pavement distress or failure to be determined.

2.1.2.1 Historical Records. Many transportation agencies maintain very detailed records of construction and maintenance operations performed on the roads and streets within their jurisdiction. This information can be extremely valuable to the pavement engineer who is charged with the task of investigating and recommending corrective actions for the rehabilitation or reconstruction of deficient pavement structures. The data from these records can provide insight into the type and amount of paving materials that should exist on the roadbed, as well as a chronological listing of maintenance and rehabilitation operations performed on the pavement during its service life.

This type of historical information can be obtained from three different types of records: design; construction; and maintenance. The design records, when they exist, should contain information that was used in the original design process. Input variables and design parameters, such as expected traffic conditions (loads and volumes), climatic conditions and available materials, should be delineated. Data concerning subgrade soil type(s) and associated strength characteristics is of particular interest. The records should also indicate design pavement layer thicknesses, as well as the types and sources of materials to be used.

The construction records can provide even more pertinent information. Most projects under contract require that detailed reports and documents be

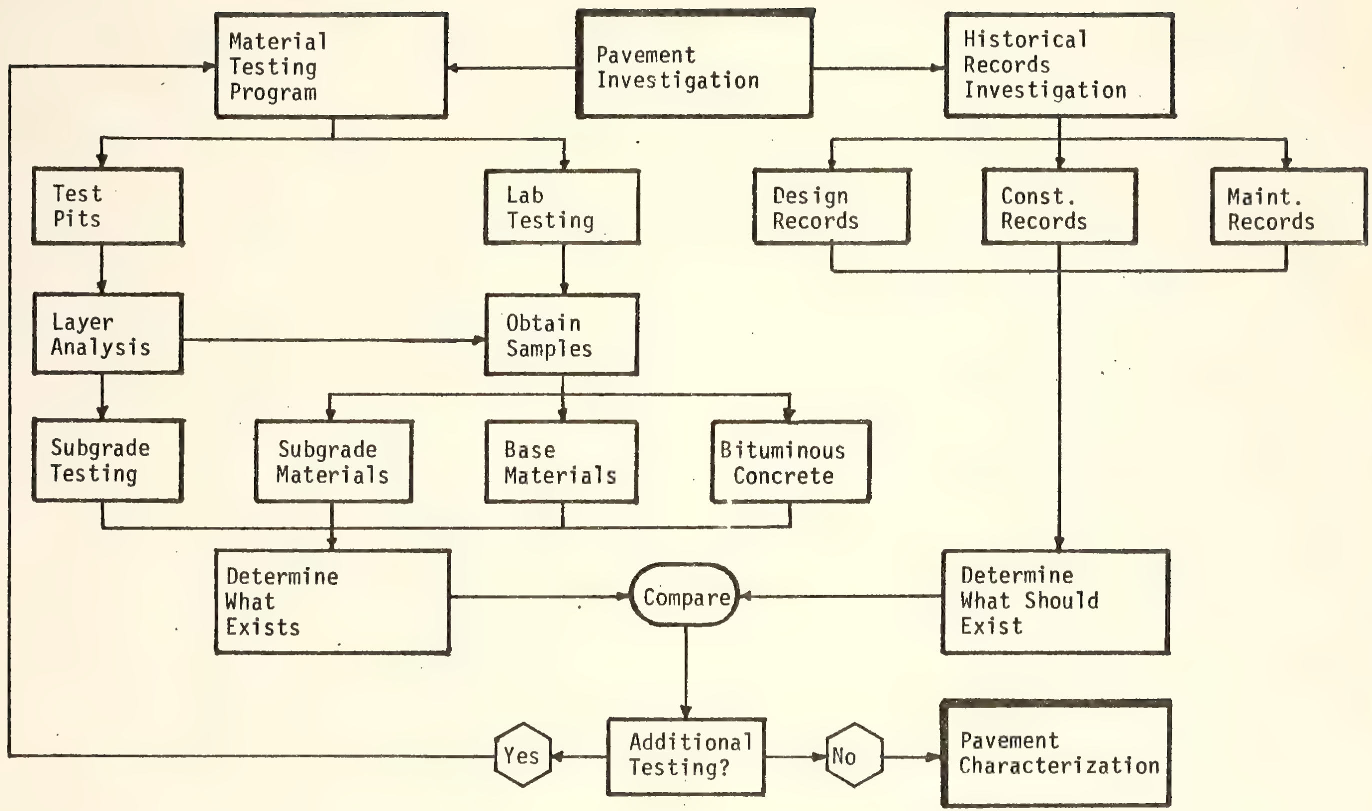


Figure 2-16 Historical Records and Materials Testing Program

prepared during construction. This information totally describes the construction methods employed, the materials utilized and the condition of the final product, as built. Such information, as listed below, should be very useful in the pavement characterization process.

Subgrade - preparation, stabilization, compaction

Base - type of material, material properties, gradation, stabilization, compaction

Bituminous Concrete - type of material, method of construction, thickness, compaction

Asphalt Binder - type, material properties, source, rate of application

Aggregate - gradation, material properties, source, blend, rate of application

In many cases, the owning agency requires the contractor to submit "as built" drawings that accurately record the changes incorporated in the final project. This information would be very valuable in characterizing the existing pavement.

The third type of records that provide pavement characterization information is maintenance records. In most cases good records should exist that indicate the timing and type of maintenance action performed, as well as the reason for the maintenance action. The type and quantities of materials used, as well as the extent of application, should indicate what materials, in addition to the originally constructed pavement, should be encountered during rehabilitation operations.

2.1.2.2. Materials Testing Program. The materials testing program is used to characterize and evaluate the materials that comprise the existing pavement structure. Representative samples from the subgrade, base and

bituminous-bound layers should be characterized using a variety of standardized tests. These tests will indicate the types of materials that actually exist in the pavement structure and will evaluate their condition.

Most of the material testing should be conducted in the laboratory, on field gathered samples from the existing pavement. However, the use of a test pit allows the pavement materials, particularly the subgrade materials, to be tested in-place. The test pit is normally a rectangular excavation that is made in the existing pavement structure. As the pavement is being excavated, samples of the pavement components should be obtained for further testing in the lab. The test pit also allows actual pavement layers to be exposed and measured. If the test pit is properly situated, surface crack propagation into lower layers can also be checked.

The major advantage of a test pit is the ability to measure in situ subgrade properties. Of particular importance is subgrade strength. ASTM D-1195, "Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements", specifies the testing procedures that should be used to measure subgrade strength. In situ density and moisture content should also be measured. ASTM D-1556, "Density of Soil In-Place by the Sand Cone Method", can be used for density and moisture content measurements. Alternatively, in situ density and moisture content can be measured by nuclear methods, as specified in ASTM D-2922 (density) and ASTM D-3017 (moisture content).

However, test pits are quite costly, as they require considerable effort. The use of test pits should be restricted to those cases where very little information is obtained from historical records, or where deficient subgrade conditions are expected. Most material characterization and testing should be accomplished in the laboratory. Pavement cores (2 to 10

inches in diameter) and sack samples (materials obtained from pavement openings and excavations) are the major sampling methods that should be used to obtain representative pavement materials.

The laboratory testing program is divided into three major areas of testing: A. subgrade materials; B. base materials; C. bituminous concrete materials.

A. Subgrade Materials - The subgrade material testing program consists of soil characterization and determination of strength properties. The tests that should be conducted to characterize the subgrade materials are:

Sieve Analysis	ASTM C-136
Liquid Limit	ASTM C-423
Plastic Limit and Plasticity Index	ASTM D-424
Moisture Density Relations	ASTM D-698 (5-1/2 lb hammer) or ASTM D-1557 (10 lb hammer)

The subgrade strength should be determined by either the California Bearing Ratio (CBR) Method (ASTM D-1883) or the Resistance R-Value Method (ASTM D-2844).

B. Base Materials - The base material testing program is similar to the subgrade testing program. The tests that should be conducted to characterize the base material are:

Sieve Analysis	ASTM C-136
Unit Weight	ASTM C-29
Specific Gravity - Coarse Aggregate	ASTM C-127
Fine Aggregate	ASTM C-128 (if applicable)
Moisture Density Relationships	ASTM C-698 (5-1/2 lb hammer) or ASTM D-1557 (10 lb hammer)

The sieve analysis is used to determine the gradation of the base materials as it now exists. From this test, it is possible to determine if any aggregate degradation has occurred during the service life of the pavement, or if any intrusion of subgrade fines into the base materials has occurred. Obviously, in order to make this determination, some information regarding the gradation of the base, as originally constructed, is needed. This may be obtained from historical records such as field gradation analysis or standardized aggregate gradings. Standardized aggregate gradings are listed in ASTM D-448.

The strength properties of the base aggregate should be determined by either the California Bearing Ratio (CBR) Method (ASTM D-1883) or the Resistance R-Value Method (ASTM D-2844).

If the pavement is located in an area where frost heave is a problem, the base material should be evaluated for frost susceptibility. The amount of material finer than the No. 200 sieve is a good indicator of frost susceptibility [241]. One of the following tests should be conducted to determine the amount of very fine particles: ASTM D-1140, ASTM D-422, or ASTM D-117.

C. Bituminous Concrete - The testing program for the bituminous concrete materials is divided into two main areas: 1. tests that are used to characterize and evaluate the existing bituminous concrete; 2. tests that

are used to characterize and evaluate the asphalt and aggregate components of the bituminous concrete.

In order to evaluate the existing bituminous concrete, full depth pavement cores or sawn samples should be obtained. ASTM specification state the minimum diameter of cores or the minimum width of sawn samples should be at least 4 times the maximum aggregate size in the bituminous concrete.

The cores of samples are used to measure bituminous concrete properties. The thickness of the asphalt-bound layer can be measured directly from the cores. Bulk specific gravity tests (ASTM D-1188 or ASTM D-2726) should be conducted on the cores or samples. If the pavement is composed of multiple bituminous concrete layers, each layer should be separated from the core and evaluated separately for bulk specific gravity. However, ASTM specifications stipulate that the minimum thickness of the core or sample layer should be 1-1/2 times the maximum size of aggregate contained within the layer. A determination of the percent of air voids in each layer (if possible) should be made (ASTM D-3203). This test is particularly important if flushing or bleeding is evident in the existing pavement.

The cores, sawn samples or sack samples are also used to determine bituminous concrete component properties. The asphalt and the aggregate properties should be determined collectively for the entire pavement thickness, as well as for each distinct bituminous layer. In order to divide the sample material into its component parts, as well as determine the asphalt content of the sample, an asphalt extraction (ASTM D-2172) should be accomplished.

The aggregate fraction should be characterized by a sieve analysis (ASTM C-136). The unit weight of the aggregate should be determined according to ASTM C-29. If aggregate polishing is a problem with local aggre-

gates, surface course aggregates should be measured for abrasion resistance using ASTM C-131.

The asphalt material extracted from the bituminous concrete should be recovered and characterized. The Abson Method should be used to recover the asphalt (ASTM D-1856). The tests listed below should be used to characterize the recovered asphalt:

Penetration	ASTM D-5
Ductility	ASTM D-113
Softening Point	ASTM D-36
Viscosity - Saybolt Furol	ASTM D-88
or	
Kinematic	ASTM D-2170
or	
Absolute	ASTM D-2171

If it is suspected that diluents from previously used cutback asphalts still exist in the bituminous concrete, a test to determine the percentage of volatiles should be conducted (ASTM D-1461 or AASHTO T-110).

When the material testing program is completed, the findings of the historical records investigation should be compared with the results of the materials testing program. If the results of the materials testing program substantiates the findings of the historical records, with regard to the type, quantities and material properties and characteristics of the existing pavement, no further sampling and testing is needed. However, if substantial differences exist, more material sampling and testing should be concluded.

The variability within the material testing program should also be investigated. If the preliminary findings of the testing program do not allow the materials to be characterized with any degree of certainty, further

testing should be conducted to adequately evaluate the material and to better define the material variability associated with the existing pavement.

2.2 Probable Cause of Distress or Failure

The pavement investigation process composed of the Field Survey Program and the Historical Records Investigation and Materials Testing Program, allows the pavement to be fully characterized and evaluated for rehabilitation needs. The Field Survey Program investigates the level of service that the pavement is providing to the user, as well as providing a formal means to evaluate the pavement's geometric adequacy, surface condition and structural adequacy. The Historical Records Investigation provides data on the type and amount of materials that should be contained within the existing pavement structure. The Materials Testing Program either substantiates the findings of the records search, or independently determines the types and amounts of materials that actually exist within the pavement structure. The laboratory testing program also allows the pavement materials to be fully characterized. Combining the results of these two programs, the existing pavement deficiencies or failures can be fully characterized and evaluated, allowing the rehabilitation needs to be identified.

The probable cause(s) of distress or failure must be identified before a method is selected to rehabilitate or reconstruct the existing pavement. The reason a pavement fails or displays signs of distress can be attributed to at least one of the reasons listed below [125]:

1. Inadequate design
2. Inadequate materials
3. Inadequate subgrade support
4. Inadequate construction methods

The specific mechanism (cause) of distress must be determined in order to determine the probable cause of failure or distress. These distress causing mechanisms can be classified into the following groups:

1. Subgrade
2. Base
3. Bituminous Concrete
4. Material Properties
5. Construction
6. Traffic

Within each group, specific distress mechanisms (causes) produce specific distress manifestations (problems). This is illustrated in Table 2-8 where the specific causes of distress are tabulated. The possible manifestations that can occur are listed for each distress mechanism. Table 2-9 lists distress manifestations and associated distress mechanisms. The use of Table 2-8 or 2-9 makes it possible to determine the probable cause(s) of distress or failure. Findings of the Field Survey Program can be used to determine possible distress manifestations (Table 2-9). Data from the Material Testing Program can be used to determine possible distress mechanisms or causes of specific pavement failures (Table 2-8). The ability to determine the probable cause of failure is enhanced through the use of this dual entry process.

2.3 Identification of Rehabilitation Alternatives

Identification of the probable cause of failure makes it possible to determine what corrective action(s) should be undertaken to restore the pavement to a desired level of service. The pavement rehabilitation alternatives that are available are quite extensive. However, the alternatives can be classified into two categories: conventional rehabilitation

Table 2-8 Distress Mechanisms

Distress Mechanism	Distress Manifestation (keyed to Table 5-9)
1 Subgrade	
A Unstable Material	IA IIE
B Settlement	IB IIB IIG
C Deep Soil Movement	IC
D Volume Changes of Material	IC IE IIB
E Water in Subgrade-Poor Drainage	IB IIF IIIA
F Swelling of Expansive Soils	IIC
G Frost Heave	IB IC IIC
H Spring Melt	IIF IIIA
2 Base	
A Excessive Deflection	IA IIG
B Volume Changes	IE IIB
C Poor Drainage	IB IIF IIIA
D Frost Action	IB IC IIC
3 Bituminous Concrete	
A Excessive Deflection	IA IIG
B Fatigue-Inadequate Thickness	IA IC ID IIF IIIA
C Surface Course Shrinkage	IB IC ID
D Soft Asphalt Surface	IG
E Unstable Mixes	IG IIA IIC IID IIE IVC
F Volume Changes in Material	IE
G Layer Consolidation	IIA IIG IVC
H Lack of Interlayer Bond	IG IID
4 Materials	
A Frost Suseptable Materials	IB IC IIC
B Low Asphalt Content	IIF IIIA IIIB
C High Asphalt Content	IE IVA
D Low Penetration Asphalt	IE
E High Penetration Asphalt	IID
F Loss of Asphalt	IIIC
G Aging of Asphalt	ID IIIC
H Loss of Asphalt Ductility	ID

Table 2-8 (continued) Distress Mechanisms

Distress Mechanism	Distress Manifestation (keyed to Table 5-9)
4 Materials (continued)	
I Improper Mix Proportions	IE
J Polish Suseptable Aggregate	IVB
K Too Many Fines in the Mix	IIC IIF IIIA
L Volume Changes in Fines	IE
M Thermal Changes	IE
5 Construction	
A Improper Fill Compaction & Fill Settlement	IC IIG
B Inadequate Base Compaction	IA
c Inadequate Bit. Concrete Compaction	IIA IIIB IVC
D Sliding of Side Slopes	IB IC
E Inadequate Lateral Edge Support	IB
F Poor Construction Joint	IC
G Lack of Liquid Asphalt Aeration	IIe
H Cold or Wet Weather Construction	IIIB
I Overheating of Mix	IIIB
J Uneven Spraybar Application	IIIB
K Inadequate Overlay Preparation	IG IIB
L Reflection or Improperly Filled Cracks	ID IF
M Movement of Underlying PCC	IF
6 Traffic	
A Traffic Action	IIIB IIID IVB
B Lack of Traffic	IE
C Excessive Loading	IA IC ID IIF IIIA
D Heavier Than Designed Traffic	IIA IIG IVA IVC
E Differential Loads Across Joints	IB
F Studded Tires	IIA IVB IVC

Table 2-9 Distress Manifestations

Distress Manifestation	Distress Mechanism (keyed to Table 5-8)
I Cracking	
A Alligator	1A 2A 3A 3B 5B 6C
B Edge Cracking	1B 1E 1G 2C 2D 3C 4A 5D 5E 6E
C Longitudinal Cracking	1C 1D 1G 2D 3B 3C 4A 5A 5D 5F 6C
D Transverse Cracking	3B 3C 4G 4H 5L 6C
E Shrinkage Cracking	1D 3F 4C 4I 4L 4M 6B
F Reflection Cracking	5L 5M
G Slippage Cracking	3D 3E 3H 5K
II Distortion	
A Rutting or Channelization	3E 3G 5C 6D 6F
B Waves	1B 1D 2B 5K
C Bumps or Humps	1F 1G 2D 3E 4A 4K
D Shoving	3E 3H 4E
E Corrugations	1A 3E 5G
F Chuckholes	1E 1H 2C 3B 4B 4K 6C
G Depressions	1B 2A 3A 3G 5A 6D
III Disintegration	
A Chuckholes	1E 1H 2C 3B 4B 4K 6C
B Raveling	4B 5C 5H 5I 5J 6A
C Weathering	4F 4G
D Abrasion	6A
IV Skid Hazard	
A Bleeding or Flushing	4C 6D
B Polishing Aggregate	4J 6A 6E
C Rutting	3E 3G 5C 6D 6F

alternatives; and recycling rehabilitation alternatives. The conventional alternatives are listed in Table 2-10, while the recycling alternatives are listed in Table 2-11. These tables also list the normal use or the type of distress that the rehabilitation alternative can correct.

In general, pavements that are in need of rehabilitation can be divided into four cases, based on the condition of the existing structure:

Case I All layers are structurally unsound.

Case II The surface layer is structurally unsound, but all sublayers are structurally sound.

Case III The surface layer and all sublayers are structurally sound, but the surface layer is functionally unsound.

Case IV All layers are sound, but the pavement is geometrically inadequate.

Obviously, the geometric inadequacy of Case IV can exist in conjunction with the conditions of Cases I, II, III.

Depending upon which case best describes the existing pavement, rehabilitation alternatives, both conventional and recycling, can be selected utilizing the information listed in Table 2-12.

The selection of rehabilitation alternatives is based upon the results of the Field Survey Program which allows the existing pavement to be classified into one of the four cases. Although this method does not address specific causes of failure or distress, it does allow a rapid determination of feasible rehabiliation alternatives.

A more precise method to identify appropriate rehabilitation alternatives, both conventional and recycling, is to use the specific distress manifestations that the existing pavement exhibits. Table 2-13 lists both conventional and recycling alternatives that are recommended for correcting

Table 2-10 Conventional Rehabilitation Alternatives

Rehabilitation Alternative	Use
Routine Maintenance	
Crack Filling	Treatment of small surface cracks
Skin Patches (Temporary)	Localized repair of cracking,
Deep Patches (Permanent)	distortion, and disintegration
Seal Coats	
Aggregate Seal	Waterproofing of surface, improvement
Fog Seal	of surface texture and skid resistance,
Emulsion Seal	renew old surfaces, retard disintegration,
Sand Seal	and seal small cracks
Surface Treatment	
Single	Waterproofing or surface, improvement
Multiple	of surface texture and skid resistance, seal cracks, retard disintegration, provide some additional strength
Overlays	
Wedge and Level	Correct distortion and restore cross-slope
Thin Overlay	Correct distortion, correct surface
Thick Overlay	deficinecies and provide added strength
Reconstruction	Removal and replacement of defective materials with new materials, improve strength and correct geometric deficiency

Table 2-11 Recycling Rehabilitation Alternatives

Rehabilitation Alternative	Use
SURFACE RECYCLING	
Heater-Planer	Correction of surface distortion, improve skid resistance, overlay preparation
Heater Scarifier	
with Rework	Correct surface distortion, skid resistance
with Remix	Correct non-load associated cracking, overlay preparation
with Overlay	Correct surface distortion, additional strength
Hot Milling	Correct surface distortion, skid resistance, overlay preparation
Cold Milling	Correct surface distortion, skid resistance, restore cross-slope, overlay preparation
CENTRAL PLANT RECYCLING	
Partial Depth Full Depth	Correction of all forms of surface distress, correction of geometry problems, correction of subgrade, base and bituminous concrete problems, and upgrading structural capacity
IN-PLACE RECYCLING	
Full Depth	Correction of geometry problems, upgrading of subgrade and base, increase in structural capacity

Table 2-12 Rehabilitation Alternatives for General Structural Condition

Structural Case	Conventional Alternatives	Recycling Alternatives
Case I All layers structurally unsound	Reconstruction Thick Overlay	Full Depth Central Plant In-Place Recycling
Case II Surface structurally unsound Sublayers structurally sound	Thick Overlay Thin Overlay	Partial Depth Central Plant Cold Milling plus Overlay Hot Milling plus Overlay Heater-Scarifier Heater-Planer plus Overlay
Case III All layers structurally sound Surface functionally unsound	Thin Overlay Surface Treatment Seal Coat Routine Maintenance	Cold Milling Heater-Planing Heater-Scarification Hot Milling
Case IV All layer sound Geometrically inadequate		
Travel Lane	Balance Widening-New Materials Unbalanced Widening-New Materials	Full Depth Central Plant In-Place Recycling
Shoulders	Reconstruction	Full Depth Central Plant In-Place Recycling
Alignment	Reconstruction	Full Depth Central Plant In-Place Recycling
Cross-section	Wedge & Leveling Overlay	Cold Milling, Hot Milling, Heater-Planer,Heater-Scarifier
Appurtenances	Reconstruct	Hot or Cold Milling

Table 2-13 Rehabilitation Alternatives for Distress Manifestations

Distress Manifestation	Conventional Alternatives	Recycling Alternatives
Cracking		
Alligator Cracks	Skin Patches Permanent Patches Provide Drainage Thick Overlays Remove &/or Upgrade Base	Partial Depth Central Plant Full Depth Central Plant In-Place Recycling
Edge Cracks	Fill Cracks Provide Drainage Improve Edge Support	Heater-Scarification Partial Depth Central Plant In-Place Recycling
Longitudinal Cracks	Fill Cracks Overlay Reconstruct Subgrade	Heater-Scarification Partial Depth Central Plant In-Place Recycling
Transverse Cracks	Fill Cracks Stress Relief Course plus Overlay	Heater-Scarification
Shrinkage Cracks	Fill Cracks Seal Coat Surface Treatments	Heater-Planing Cold Milling Heater-Scarification
Reflection Cracks	Fill Cracks Thick Overlays Stress Relief Course plus Overlay Reconstruction	Heater-Scarification Partial Depth Central Plant In-Place Recycling
Slippage Cracks	Reconstruct	Heater-Scarification Heater-Planer plus Overlay Hot or Cold Milling plus Overlay Partial Depth Central Plant

Table 2-13 (continued) Rehabilitation Alternatives for Distress Manifestations

Distress Manifestation	Conventional Alternatives	Recycling Alternatives
Distortion		
Rutting	Leveling Course plus Surface Treatment Leveling Course plus Thin Overlay Thick Overlay	Heater-Planer Heater-Scarifier Hot or Cold Milling Partial Depth Central Plant
Waves	Wedge and Level Thick Overlay	Heater-Planer Heater-Scarifier Hot or Cold Milling
Bumps or Humps	Deep Patch Thick Overlay Reconstruct Base	Heater-Planer Hot or Cold Milling In-Place Recycling
Shoving	Deep Patch Reconstruct	Heater-Planer Hot or Cold Milling
Corrugation	Leveling Course Reconstruct	Heater-Planer Hot or Cold Milling Heater-Scarification In-Place Recycling
Chuckholes	Skin Patches Deep Patches Overlay Reconstruct	Heater-Scarification Partial Depth Central Plant In-Place Recycling
Depressions	Leveling Course Thick Overlay	Heater-Scarification Partial Depth Central Plant

Table 2-13 (continued) Rehabilitation Alternatives for Distress Manifestations

Distress Manifestation	Conventional Alternatives	Recycling Alternatives
Disintegration		
Chuckholes	Skin Patches Deep Patches Reconstruction	Heater-Scarification Partial Depth Central Plant In-Place Recycling
Raveling	Seal Coats Surface Treatments Thin Overlays Reconstruction	Heater-Planer Hot or Cold Milling Heater-Scarifier Partial Depth Central Plant
Weathering	Seal Coats Surface Treatments Overlays	Heater-Planer Hot or Cold Milling Heater-Scarification
Abrasion	Thin Overlay	Heater-Planing Hot or Cold Milling

Table 2-13 (continued) Rehabilitation Alternatives for Distress Manifestations

Distress Manifestation	Conventional Alternatives	Recycling Alternatives
Skid Hazard		
Bleeding or Flushing	Hot Blotter Aggregate Thin Overlay (low asphalt content) Reconstuction	Heater-Planer Hot or Cold Milling Heater-Scarifier
Polished Aggregate	Seal Coat Surface Treatment Overlay	Hot or Cold Milling Heater-Scarifier with New Agg.
Rutting	Leveling Course plus Surface Treatment Leveling Course plus Thin Overlay Thick Overlay	Heater-Planer Heater-Scarifier Hot or Cold Milling Partial Depth Central Plant

specific distress manifestations. Entering the Table with the appropriate pavement distress enables one to identify the recommended rehabilitation alternative(s). If more than one distress manifestation is evident in the existing pavement, all rehabilitation alternatives should be identified. The recommended corrective action for the more severe distress problem will generally totally solve or aid in correcting the other, less severe distress problem.

A major factor not specifically addressed in the information contained within Table 2-13 is the degree and extent of the pavement distress. The concept of distress severity and extent of distress was previously identified in conjunction with the pavement condition surveys of the Field Survey Program. Obviously, the degree or magnitude of the distress will influence the type of rehabilitation method that can be used to restore the pavement to an acceptable level of service.

A method to assess the magnitude of the distress has been advanced by Davidson et al. [52]. According to their study, pavement distress progresses through four distinct stages: (1) The first stage of distress occurs during construction when the virgin properties of the binder are changed. This change can be attributed to the processing (particularly heating) actions that the binder is subjected to. (2) The second stage of distress is attained after several years of exposure to weathering and normal wear. Distress is evidenced by slight hairline cracks, crazing, loss of matrix, minor surface blemishes and increased permeability. Only minor maintenance or surface rejuvenation is required at this time. (3) The third stage of distress is evidenced by extreme surface wear, distortion, generally poor appearance and rideability, although the pavement is structurally sound. Corrective actions required are those operations that will

restore the surface to an acceptable level of service. (4) In the fourth stage of distress, the pavement structure has deteriorated to an extent that it no longer serves the original design purpose. Extensive aging, heavy wear and lack of sufficient maintenance all contribute to this stage of distress. The normal corrective action is to either remove and reconstruct the pavement, or to salvage and recycle the pavement components.

The concept of selecting appropriate rehabilitation alternatives for varying degrees of pavement distress is intrinsically addressed in Table 2-13. The first rehabilitation alternative listed for each distress manifestation would normally be used to correct distress problems of minor severity and low frequency of occurrence (2nd and 3rd stage distress problems). On the other hand, the rehabilitation alternative listed last would normally be used to correct pavement distress of major severity and extensive frequency of occurrence (4th stage distress problems).

No quantitative values are assigned to the different degrees of distress and associated rehabilitation alternatives addressed in Table 2-13. The condition survey should provide enough information to subjectively determine the severity and extent of the pavement distress. The selection of an appropriate rehabilitation alternative should be based on sound engineering judgement using all available information. In most cases, the process of using engineering judgment, based upon personal knowledge, past experience and local conditions will better identify rehabilitation alternatives than a strict quantitative process.

Another procedure that can be used to identify feasible recycling rehabilitation alternatives is a method that considers pavement distress mechanisms. Each distress mechanism listed in Table 2-14 has appropriate and feasible recycling options identified. As was the case with the selection

process outlined in Table 2-13, engineering judgment must be used to narrow the choice of possible alternatives so that an appropriate recycling method(s) can be selected for the degree of distress that the existing pavement exhibits.

A flow chart of the rehabilitation selection process is illustrated in Figure 2-17 (conventional alternatives) and Figure 2-18 (recycling alternatives).

All three processes (general structural classification, distress manifestation and distress mechanism) should be used to identify possible rehabilitation alternatives. Those alternatives that are indicated as feasible alternatives by all three processes, should be considered as prime candidates for further evaluation. Alternative methods indicated by only one or two of the processes should be carefully considered, but, if inappropriate or unrealistic for existing pavement conditions, they should be discarded in favor of more realistic alternatives. Each rehabilitation alternative identified should be considered in light of the magnitude of pavement distress displayed. Alternative methods that are obviously inappropriate for the degree of distress displayed should be eliminated from further consideration.

2.4 Selection of Rehabilitation Method

The most appropriate corrective action(s) must be selected from the feasible alternatives generated by the Rehabilitation Identification Process. Although all alternative methods identified could satisfactorily rehabilitate the pavement, normally one (or more) of the methods is more desirable.

The choice of a conventional rehabilitation method is not normally a problem. Most agencies have considerable knowledge and widespread experience with conventional rehabilitation processes, which allows the appropri-

Table 2-14 Recycling Alternatives for Distress Mechanisms

Distress Mechanism	Recycling Alternative: Heater-Planer without Overlay	Heater-Planer with Overlay	Heater-Scarifier with Rework	Heater-Scarifier with Remix	Heater-Scarifier with Overlay	Hot Milling without Overlay	Hot Milling with Overlay	Cold Milling without Overlay	Cold Milling with Overlay	Patial Depth Central Plant	Full Depth Central Plant	In-Place
Subgrade												
All Cases											X	X
Base												
All Cases											X	X
Bituminous Concrete												
Excessive Deflection				X	X		X		X	X		X
Fatigue				X	X		X		X	X		
Surface Course Shrinkage		X	X	X	X		X		X	X		
Soft Asphalt Surface		X		X	X		X		X	X		
Unstable Mixes		X		X	X		X		X	X		
Volume Changes in Material		X	X	X	X		X		X	X		
Layer Consolidation	X	X	X	X	X	X	X	X	X	X		
Lack of Interlayer Bond	X	X	X	X	X	X	X	X	X	X		
Materials												
Frost Suseptable Materials										X	X	X
Asphalt Content (low or high)			X	X						X	X	X
Asphalt Penetration			X	X						X	X	X
Loss of Asphalt			X	X						X	X	X
Asphalt Ductility			X	X						X	X	X
Mix Proportions			X	X						X	X	X
Polishing Aggregate	X	X	X	X	X	X	X	X	X			
Excess Fines in Mix	X	X	X	X	X	X	X	X	X	X		
Volume Change in Fines		X	X	X	X		X		X	X		
Thermal Changes		X	X	X	X		X		X	X		

Table 2-14 (continued) Recycling Alternatives for Distress Mechanisms

Distress Mechanism	Recycling Alternative: Heater-Planer without Overlay	Heater-Planer with Overlay	Heater-Scarifier with Rework	Heater-Scarifier with Remix	Heater-Scarifier with Overlay	Hot Milling without Overlay	Hot Milling with Overlay	Cold Milling without Overlay	Cold Milling with Overlay	Parital Depth Central Plant	Full Depth Central Plant	In-Place
Construction												
Inadequate Fill Compaction											X	X
Inadequate Base Compaction											X	X
Inadequate Bituminous Compaction	X		X			X		X		X	X	X
Sliding of Side Slopes											X	X
Inadequate Edge Support											X	X
Poor Construction Joint			X							X		X
Lack of Aeration-Liquid Asphalts	X		X			X		X			X	X
Cold or Wet Weather Construction	X		X			X		X			X	X
Overheating of Mix	X		X			X		X			X	X
Uneven Spray Bar Application	X		X	X		X		X				
Inadequate Overlay Preparation	X		X			X		X				
Reflection of Cracks			X	X	X					X		X
Movement of Underlying PCC						X		X			X	X
Traffic												
Traffic Action	X		X			X		X		X		X
Lack of Traffic		X	X	X	X		X		X			
Excessive Loading							X		X	X	X	X
Heavier than Designed Traffic										X	X	X
Differential Loads Across Joint										X	X	X
Studded Tires	X		X			X		X				

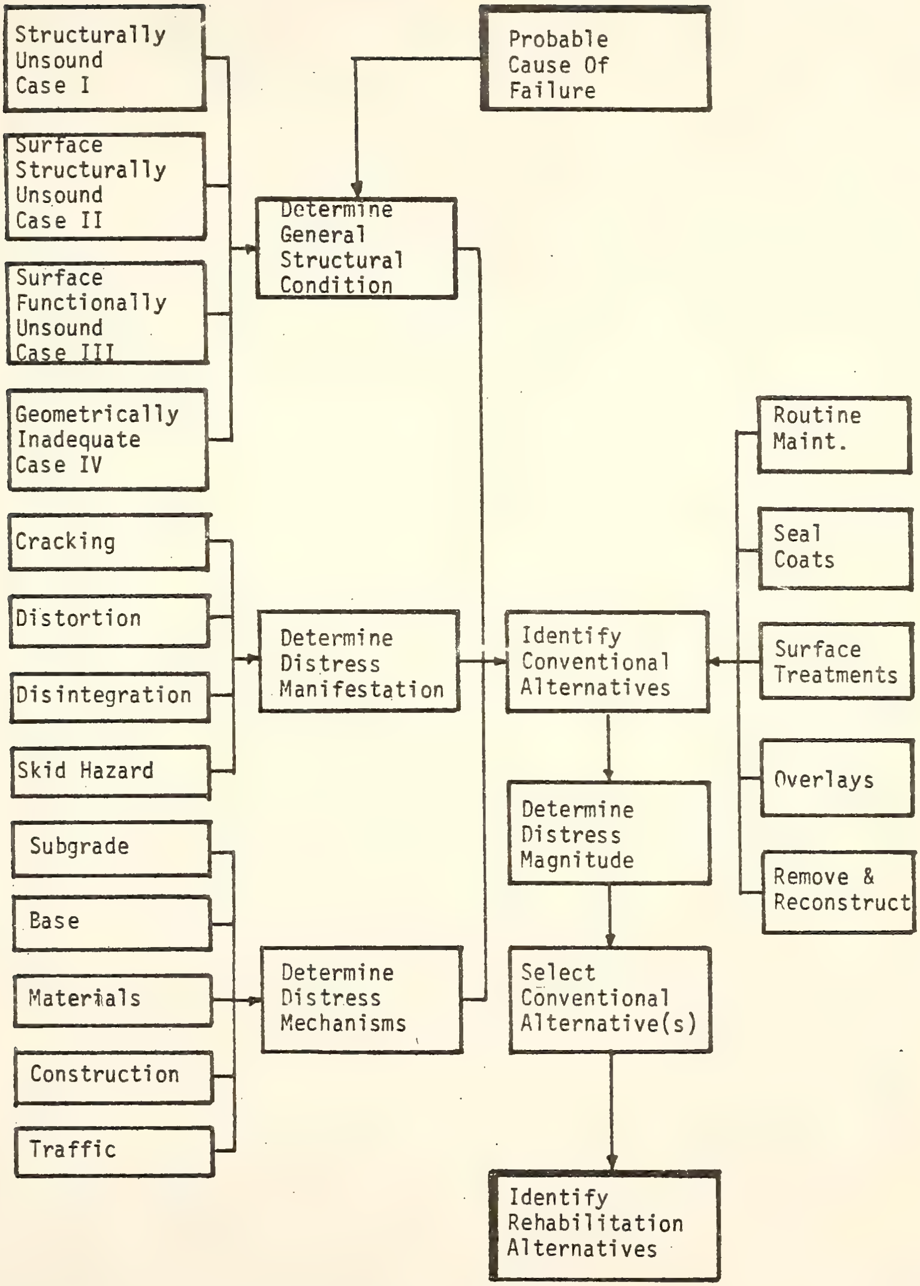


Figure 2-17 Conventional Rehabilitation

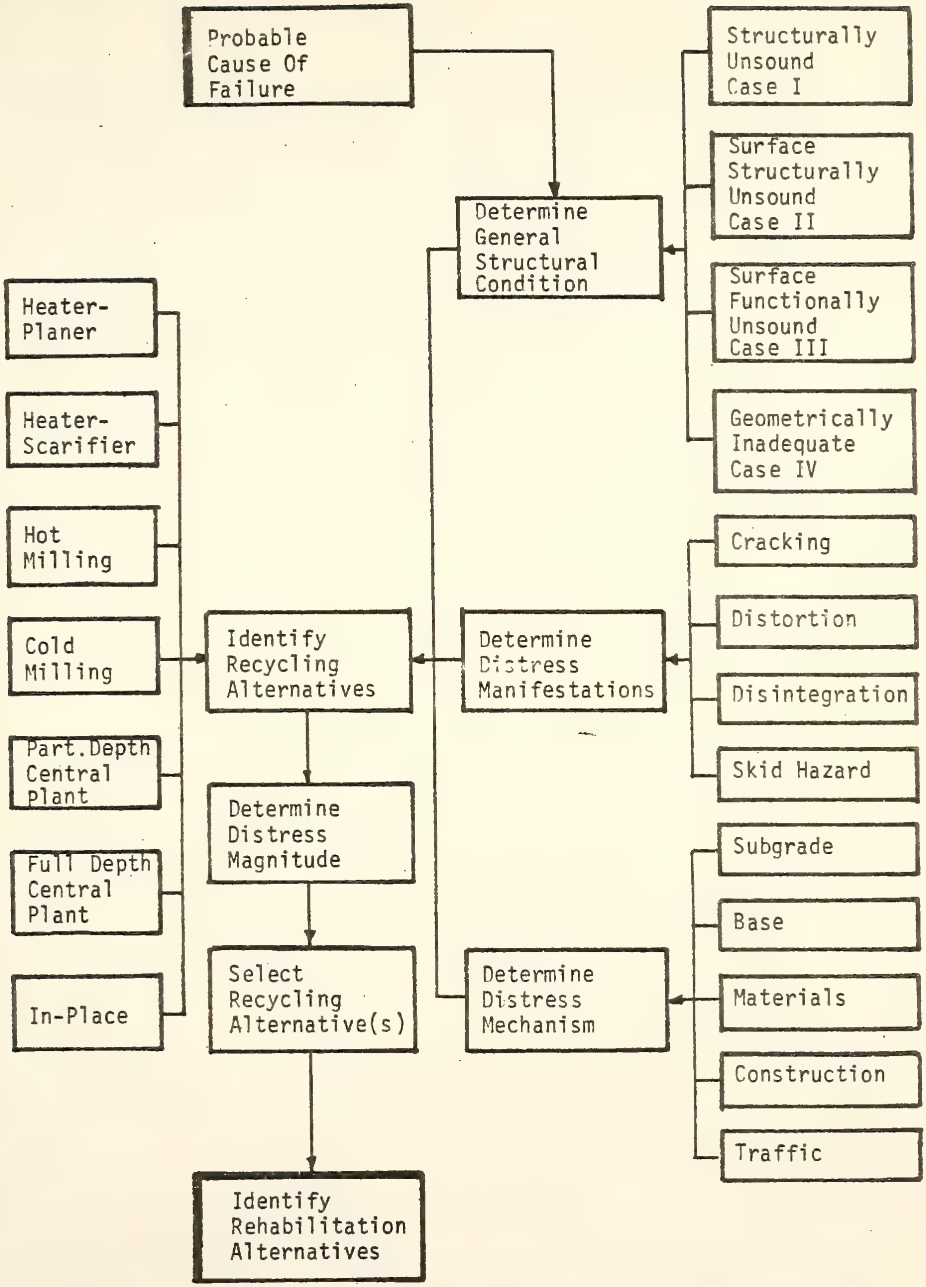


Figure 2-18 Recycling Rehabilitation

ate method to be selected with a minimal amount of difficulty.

However, the choice of a recycling rehabilitation method is not as easy. Most agencies have limited knowledge of, and little experience with, recycling processes. To the inexperienced it might appear that several recycling alternatives are equally desirable, when in fact, one method is more appropriate for the pavement conditions being considered.

Several factors, other than the distress mechanisms and manifestations, should be considered when selecting the appropriate recycling alternative. These factors and their influence on the choice of the appropriate recycling method are illustrated in Table 2-15.

The thickness of the existing bituminous-bound material is an important factor to consider if surface recycling (hot or cold) or partial depth central plant recycling is indicated.

The environmental setting (urban, suburban, rural) or location of the pavement structure also influences the choice of recycling method. Some recycling methods are preferred or are more suited for one environmental setting than another location. The information in Table 2-15 comments on the frequency of use of each recycling method for the respective environmental setting listed.

The functional classification of the highway influences the choice of the appropriate recycling method. Certain recycling methods are more desirable because of the roadway's importance to the entire highway system, the magnitude and type of traffic using the road, and the ability of the highway to tolerate reconstruction activities. The tabulated information comments on the frequency of use of each recycling method for the respective roadway functional classification.

Table 2-15 Other Factors Influencing the Choice of Recycling Method

		Hot Surface Recycling	Cold Surface Recycling	Partial Depth Central Plant Recycling	Full Depth Central Plant Recycling	In-Place Recycling
Minimum Layer Thickness Requirements		Yes	Yes	Yes	No	No
Frequency of Use by Highway Location	Urban	Common	Common	Limited	Rare	Rare
	Suburb	Common	Common	Limited	Limited	Rare
	Rural	Limited	Limited	Common	Common	Common
Frequency of Use By Highway Functional Classification	Freeway	Limited	Common	Limited	Limited	Rare
	Artery	Common	Common	Limited	Limited	Limited
	Collector	Common	Common	Limited	Limited	Limited
	Local	Common	Limited	Rare	Rare	Limited
Traffic Disruption		Minimual	Minimal	Moderate	Maximum	Maximum
Climatic Effect on Construction Season		Adverse	Minimal	Moderate	Moderate	Adverse
Typical Project Size		Small-Medium	Small-Large	Medium-Large	Medium-Large	Small-Large
Typical Project Duration		Short	Short	Average	Long	Long
Compliance with Environmental Standards-Difficulty		Moderate Great	None	Moderate Great	Moderate Great	None

Another important consideration in choosing the appropriate recycling alternative, is the degree to which traffic will be disrupted while the pavement is being reconstructed. Surface recycling results in the least amount of disruption, while full depth central plant and in-place recycling cause the maximum disruption. In fact, these latter two alternatives normally require that traffic be totally banned from the roadway.

Climatic conditions can seriously restrict the construction season to a time of the year when favorable weather conditions are encountered. The degree to which weather affects the recycling operations can be an important decision criterion for some geographic areas. The effect that weather has on each recycling alternative is listed in Table 2-15.

The physical size of the total rehabilitation effort can also influence the choice of an appropriate recycling method. Table 2-15 comments on project size and the normal use of recycling methods.

Total project duration may also influence the choice of the recycling method. Typically, surface recycling operations are associated with short project durations, while the project duration for central plant and in-place recycling jobs are normally longer.

The existence and enforcement of local environmental standards and laws will also influence the choice of the appropriate recycling method. Hot surface recycling and central plant recycling can pose problems in complying with pollution standards.

The feasible alternatives generated by the Rehabilitation Identification Process should be narrowed to two choices. In one case, the most appropriate conventional alternative should be chosen based on experience, familiarity and applicability of the process. In the other case, an appropriate recycling alternative should be chosen from among the feasible al-

ternatives by the use of the factors listed in Table 2-15. However, the final choice of a single method will be based on an analysis of the economics, energy consumption and ecological ramifications of each rehabilitation alternative. Before this analysis can take place, a mix design, as well as a pavement design for the recycled pavement must be undertaken.

2.5 Mix Design

The design of the recycled asphalt concrete mixture is very important to the success of the rehabilitation process. Appropriate design procedures should be used for the various recycling methods, for each form of recycling requires a different procedure.

2.5.1 Surface Recycling

The only form of surface recycling that requires a recycled mixture design is heater-scarification. The major concern of the heater-scarification mix design process is the choice of the type and amount of modifying material to be added during the scarification process.

The design procedure is a trial and error process. The objective is to choose a modifier and determine the proper amount of the modifier needed to change the existing binder characteristics to a predetermined value. The choice of a modifier is very subjective, for many different modifying agents are available. The basic modifiers are either liquid asphaltic materials or proprietary rejuvenating or softening materials. Some research has been conducted to evaluate different modifying agents for recycling purposes [9]; however, the choice is very subjective.

The determination of the proper amount of modifying agent is more precise [5,107]. Samples (either cores or sack) of the pavement to be heater-scarified should be obtained. A layer, 3/4 to 1 inch thick, should be re-

moved from the top of the samples. The binder in this upper layer should be extracted and recovered using standard procedures. Several different blends of the extracted binder and varying percentages of the modifying agent should be evaluated. The viscosity or the penetration of the blend should be measured for at least three different blends of modifier and reclaimed asphalt cement. The viscosity or penetration and the percentage of modifier in the blend should be plotted. (Plot should be made on semi-log paper with the viscosity or penetration plotted on the ordinate (log scale) and the percentage of modifier on the abscissa.) A straight line (or slightly curved line) connecting graph points should be drawn. The amount of modifier required for the recycled mixture is determined by entering the graph with the final specified viscosity or penetration of the recycled blend and reading the corresponding percentage of modifier needed.

The amount of modifier required will be affected by the timing of its application during the heater-scarification process. If the modifier is applied immediately following scarification, the amount determined by the blending graph should be accurate. However, if the modifier is applied after compaction, the blending graph is not applicable. Small, scarified samples of the pavement material should be fabricated, compacted and sprayed with modifier to simulate the recycling process. The samples should be checked to determine how well the modifier penetrates the compacted surface and whether flushing will be a problem. If penetration and/or flushing poses a potential problem, the amount of modifier needed should be changed. According to the Asphalt Recycling and Reclaiming Association, typical application rates for heater-scarification vary between 0.1 to 0.2 gallons per square yard [131].

2.5.2 Central Plant Recycling

The mix design procedures for central plant recycling are basically the same procedures used for designing conventional hot mix asphalt concrete. In general, satisfactory mixes have been produced using slightly modified Marshall and Hveem Procedures. See Section 8.3.2 (V.II) for a detailed narrative of the design process.

Appendix A (V.II) contains a set of guidelines for design of central plant recycled mixes using Hveem or Marshall methods.

Appendix B (V.II) contains a set of guidelines for design of central plant recycled mixes using a single modifying agent.

Appendix C (V.II) contains a set of guidelines for designing central plant recycling mixes using salvaged aggregate and a single reclaiming agent.

2.5.3 In-Place Recycling

Many different methods have been used to design and test cold, mixed in-place recycled materials. These testing methods have included the Marshall Stability Test, the Hveem Stability and Cohesiometer Test, the Splitting Tensile Test and the Resilient Modulus Test.

At present, no standardized procedures exist for designing and evaluating cold, mixed in-place recycled materials. However, laboratory work conducted by Tia [231] has indicated that the gyratory compactor can be used to produce cold mixed recycled samples that accurately simulate the effects of field operations and future traffic conditions on materials recycled in-place. The gyratory compactor was found to yield the best results of all equipment tested. The Hveem kneading compactor was investigated as a possible tool, but was eliminated because of the tendency of the recycled mix to adhere to the compactor foot. The Marshall method produced samples with in-

consistent material properties and did not properly simulate actual field conditions.

Tia found that the gyratory compactor could very accurately predict future recycled mixture instability, as well as the phenomena of asphalt bleeding. The high compactive force of the gyratory machine forces the old and the new asphaltic material to act as one. This action more accurately simulates the conditions that traffic will impose on the recycled material after some period of service.

The standard ASTM procedures for use of the gyratory compactor calls for 30 gyratory revolutions at a ram pressure of 200 psi. According to ASTM procedures this is equivalent to 75 blows of the standard Marshall hammer on each side of a specimen. The standard gyratory compactive effort is supposed to be equivalent to one year of compaction under medium traffic. However, Tia found that by using 40 gyratory revolutions at a ram pressure of 200 psi, the effects of traffic could be more accurately modeled, and materials that had a tendency to bleed could be more readily identified.

The evaluation of the recycled samples were conducted using the Hveem Stabilometer to measure R and S values and the Hveem Cohesiometer to measure C values. Currently, work is underway to evaluate the use of the Resilient Modulus Test as a means of evaluating recycled mixes constructed using in-place methods.

The testing procedure developed by Tia is outlined in Appendix D (V.II).

2.6 Pavement Design

The design of the pavement cross-section is very important to the recycling process. The proper thickness of pavement components must be chosen so that the pavement will perform in an adequate manner for the anticipated

traffic conditions (magnitude and frequency of axle loads) and climatic conditions, as well as the types of materials used. To date most of the pavement design for recycled asphalt pavement materials has been done using the American Association of State Highway and Transportation Officials (AASHTO) design procedures for flexible pavements [1]. Unlike the basic Asphalt Institute design procedure [228], the AASHTO method utilizes layer coefficients to represent the relative strength of a wide variety of materials that can be used in the pavement structure.

The original AASHO coefficients were developed from the AASHO Road Test conducted in Ottawa, Illinois in the late 1950's and the early 1960's. Presently, a considerable amount of research is underway to define appropriate layer coefficients for recycled products. In the interim, sound judgment should be used to select representative layer coefficients for recycled pavement design.

The AASHTO Design Process relates the number of 18-kip single axle load repetitions required to reach a predetermined terminal serviceability level for any given pavement structure, climatic condition and subgrade soil. An excellent discussion of the background and procedures of the AASHTO method is contained in <u>Principles of Pavement Design</u> by Yoder and Witczak [241]. The AASHTO Design procedure is outlined in Appendix E (V.II).

The AASHTO Method specifies that the minimum thickness for surface, base and subbase courses should be 2, 4, and 4 inches, respectively. Each layer should also be checked to insure that it is not overstressed. This process will also result in another set of minimum layer thicknesses.

Due to the lack of data correlating field performance with recycled asphalt concrete mixture characteristics, detailed information regarding the selection of appropriate layer coefficients is lacking. Most of the recy-

cled pavement design has been accomplished using layer coefficients chosen on the basis of sound engineering judgment. The correlation of material properties with layer coefficients (see Appendix E (V.II)), as well as the layer coefficients developed by the Forest Service [71], have been used as a basis for this engineering judgment. Obviously, the method of recycling will greatly influence the choice of layer coefficients.

2.6.1 Surface Recycling

The pavement design process for surface recycling is quite simple. As long as the pavement is structurally adequate, the only design consideration is the appropriate thickness of overlay (if used) that should be applied to the recycled surface. Because the bond between the recycled surface and the overlay is extremely tight [233], much thinner than normal overlays can be applied. The Asphalt Institute recommends that the minimum thickness be no less than twice the maximum particle size in the overlay [222]. One transportation agency (Texas) specifies that the minimum overlay thickness be not less than 0.4 to 0.5 inches [26]. If the overlay must serve the function of increasing the structural number of the pavement, most agencies have assumed an overlay coefficient appropriate for the type of material being used. The Mississippi State Highway Department has used 0.44 as the AASHTO layer coefficient for virgin material hot mix overlays for surface recycling [236].

2.6.2 Central Plant Recycling

Most of the pavement design for central plant recycled materials has been accomplished using the standard AASHTO layer coefficients for high stability plant mix material. Because the quality of central plant recycled mixes can be carefully controlled and a uniform product of near new material

characteristics can be formed, this assumption appears to be sound. The Arizona Department of Transportation has found that Hveem correlated structural layer coefficients for 5 recycling jobs has ranged from .36 to .42 [5]. Arizona assumes a recycled layer coefficient of 0.40 for central plant recycled mixtures [201]. Initially, the recycled material on a central plant recycling job in Oregon was assumed to have a layer equivalency of 2.0 times Oregon's crushed base equivalent [60]. (This value is similar to the AASHTO coefficient for high stability plant mixed materials.) However, after a period of service and Dynaflect testing, it was determined that appropriate equivalency was 1.7 or 1.6. This would indicate that the AASHTO layer coefficient for high stability plant mixes should also be reduced by the same order of magnitude. The Asphalt Institute, in an article discussing the effects of recycling on a road's traffic capacity [239], used an AASHTO layer coefficient of .35 for central plant recycled material. Until more field correlated data is available, it would seem to be appropriate to assign a layer coefficient to central plant recycled material that is lower than the AASHTO coefficient value (0.44) for high stability plant mixes. However, since the amount of reduction cannot be quantified, the reduction should be based on sound engineering judgment.

2.6.3 In-Place Recycling

Due to the wide variety of recycled products that can be produced by in-place recycling, the choice of appropriate layer coefficients is more difficult and subject to more engineering judgment than other recycling methods. However, a sound basis on which to select appropriate layer coefficients is the information developed by the Forest Service [71]. The coefficients published by the Forest Service cover a wide range of materials and construction methods and can be used to identify a range of values that can

be assigned as layer coefficients. The appropriate coefficients can be selected based on the materials and the construction method used, as well as sound engineering judgment.

A layer coefficient for the recycled material was assumed to be 0.22 on an in-place recycling project in Maine, where the existing pavement was crushed with a hammermill and placed as base material (with no additional binder added) [179]. This value was considered reasonable for low stability mixes. (If 4% emulsified asphalt had been added to the salvaged material it was felt that the appropriate layer coefficient would have been .25.)

An in-place recycling project in Elkhart County, Indiana that used a chemical in the crushing and pulverization process, as well as additional asphalt, in the form an emulsion, assumed an appropriate range of layer coefficients from 0.16 to 0.20 [62].

Obviously the choice of appropriate layer coefficients for in-place recycled materials, until completely researched and field tested, must rely, in large part, on the pavement engineer's experience and judgment.

An important in-place recycling consideration is the need for the recycled product to be overlayed with some form of waterproofing or wearing surface. If the pavement design does not identify the need for a structural overlay, most agencies have recommended that, depending on the anticipated traffic, either a thin hot mix overlay or a surface treatment (multiple or single) be applied over the recycled material.

CHAPTER THREE

CONSTRUCTION GUIDELINES

The final phase of the recycling improvement process involves implementing the solution generated by the recycling guidelines for the rehabilitation or reconstruction of the deficient pavement. The recycling system (Figure 2-18) should be fully evaluated and compared with the conventional system (Figure 2-17) identified by the recycling guidelines. Prior to the start of actual construction, the job should be thoroughly analyzed and planned. Anticipated problems should be identified and remedial solutions generated in advance of actual occurrence. Finally, a set of specifications should be developed to adequately control work activities and to insure that a quality product is produced.

3.1 Formulation of a Recycling System

The recycling alternative generated by the recycling guidelines is only a generalized recycling method. In order to implement the solution, a specific recycling system must be chosen. The system will be composed of component pieces of equipment selected to optimize system performance. The recycling guidelines will provide input for the equipment selection process so that the proper equipment components will be identified. The characterization of the existing pavement, the recycled mix design and the design of the recycled pavement will greatly influence the choice of equipment. The availability of equipment will also influence the selection of equipment components for the recycling system. In many cases the presence or absence

of one vital piece of equipment may influence the selection of the rest of the system components.

Equipment selection charts, illustrated in Tables 3-1, 3-2 and 3-3 will aid in the selection and formulation of the recycling system. Each chart lists the general processes or operations associated with each form of recycling. Corresponding to each process, is a list of process equipment and a list of support equipment. The process equipment consists of those pieces of machinery needed to perform the actual recycling operation. The support equipment are those pieces of machinery needed to assist in the recycling operation. Proper use of the charts will allow the required equipment to be identified and, where applicable, will identify alternative machinery that can be used. Where alternative choices exist, selection should be based on the type of machine that best fits the project conditions (and/or the contractor's access to the appropriate machine).

The component pieces of equipment required for surface recycling are listed in Table 3-1. The selection of process and support equipment is straightforward, since the choice is dictated by the general recycling method identified by the recycling guidelines. However, it should be noted that, in some instances, the need for some equipment is questioned. For these particular cases, specific models of equipment or construction methods will dictate whether the questioned equipment is needed.

Heater-planers, hot millers and cold millers that do not have an integral elevating conveyor system will require auxiliary equipment to remove and load the planed or milled material. A separate distributor may be required for some heater-scarification processes if the heater-scarifier does not have an integral additive system. Additional trimming equipment may be needed for both hot and cold milling processes if the street being milled

Table 3-1 Surface recycling Equipment.

Process	Process Equipment	Support Equipment
Heater-Planing	Heater-Planer	Street Sweeper Elevating Equipment (?) Front End Loader Windrow Elevator Haul Trucks
Heater-Scarification with Rework	Heater-Scarifier Distributor (?) Compaction Equipment	Street Sweeper
Heater Scarification with Remix	Heater-Scarifier Distributor (?) Hot Mix Trucks Compaction Equipment	Street Sweeper
Heater-Scarification with Overlay	Heater-Scarifier Distributor (?) Hot Mix Trucks Asphalt Paver Compaction Equipment	Street Sweeper
Hot Milling	Hot Miller	Additional Trimming Equip(?) Elevating Equipment(?) Front End Loader Windrow Elevator Haul Trucks Street Sweeper
Cold Milling	Cold Miller	Water Truck(?) Additional Trimming Equip(?) Elevating Equipment(?) Front End Loader Windrow Elevator Motor Grader(?) Haul Trucks Street Sweeper

contains obstructions. Additional equipment, in the form of hand tools, small milling or planing devices may be required to finish the milling operation. Cold millers that do not have an integral water system (or those with an inadequate system) may require the use of a water truck to wet the pavement surface in advance of the milling operation.

The equipment required for central plant recycling is listed in Table 3-2. The choice of recycling processes, as well as the equipment required to perform the processes, is more variable for central plant recycling than for surface recycling. Several different process combinations can be chosen to recycle pavements using central plant techniques.

Initially, a choice must be made as to the method of removing the existing pavement. Partial depth removal normally requires that some form of milling operation be used. However, if cold milling is selected, no further processing is normally required before the salvaged material is recycled. However, if hot milling is used, some additional crushing may be required. In either case, if the miller used does not have an integral material elevating conveyor system, auxiliary loading equipment will be required.

Removing the existing pavement, full depth requires that some form of ripping or scarification device be used. The choice of the equipment will depend on the existing pavement thickness and material integrity. Usually plant mixed materials must be ripped, while other materials, particularly if placed in thin lifts, can be scarified. Auxiliary equipment will be required to pick up, load and transport the ripped material if the loosened material is to be crushed using central plant techniques.

The decision to use in-place crushing and pulverization equipment is also dependent on the existing pavement thickness and material integrity. Plant mixed materials will usually require the use of a traveling hammermill

Table 3-2 Central Plant Recycling Equipment

Process	Process Equipment	Support Equipment
Payement Removal Crushing (Partial & Full Depth)	Hot Miller Cold Miller	Elevating Equipment(?) Front End Loader Windrow Elevator Haul Trucks
or		
Payement Remoayal (Full Depth Ripping)	Tractor Mntd Ripper Tractor Mntd Scarifier Grader Mntd Ripper & Scarifier	Central Plant Crushing(?) Scrapers Front End Loader Windrow Elevator Haul Truck
Crushing (In-Place)	Roller-Sheepsfoot, Segmented,Grid or Chopping Hammermill	Water Truck Elevating Equipment Scraper, Front End Loaders or Windrow Elevator Haul Trucks
or		
Crushing (Central Plant)	Jaw Crusher &/or Roll Crusher &/or Cone Crusher &/or Impact Crusher &/or	Feed Equipment Sizing Equipment Haul Trucks(?)
Mixing	Drum Mixer Batch Plant Mixer	Feed Equipment
Street Operations	Asphalt Paver Compaction Equipment	Distributor(?) Haul Trucks

for adequate crushing and pulverization.

Central plant crushing can be accomplished by any one (or any combination) of the crushers listed in Table 3-2. When the crushing operation is located at a site other than the central plant recycling site, haul trucks will be needed to transport the crushed material.

The process equipment listed for street operations ignores the preparation of the roadbed required before recycled paving operations takes place. Equipment needed for these operations should be identified. An asphalt distributor may be required for prime or tack coats.

The equipment components required for in-place recycling are listed Table 3-3. In-place recycling is the most variable of all recycling methods, and as such, the choice of process and support equipment is subject to many factors external to the actual recycling operations. Many different combinations of equipment may be chosen to form the recycling system.

The choice of equipment to loosen and remove the existing pavement depends on the thickness of the existing pavement layers, origin or type of materials and material integrity. Pavements that are 2 inches or more in thickness are normally plant mixed products and will require the use of rippers or cold millers to remove the material. Rippers should be mounted on tractors or motor graders of sufficient power to loosen high-type pavement materials. The other removal equipment, listed in Table 3-3, is normally used on low-type pavements (multiple seal coats, mixed in-place materials, etc). Although rippers may be used on low type materials, larger pieces may be generated than desired. The cold miller should be selected as a removal tool if precise, partial depth removal is required or if precisely sized pieces of salvaged material are required.

Table 3-3 In-Place Recycling Equipment

Process	Process Equipment	Support Equipment
Pavement Removal	Tractor Mntd Rippers	
	Grader Mntd Ripper	
	Tractor Mntd Scarifier	
	Grader Mntd Scarifier	
	Bucket Loaders	
	Construction Discs	
	Cold Millers	
Crushing & Pulverization	Sheepfoot Roller	Motor Grader
	Grid Roller	Water Truck
	Chopping Roller	
	Cutter-Crusher	
	Single Shaft Stabilizer	
	Multi-Shaft Stabilizer	
	Hammermill	
	Chemical-Water Distributor	
Mixing	Motor Grader	Motor Grader
	Hammermill	Water Truck
	Single Shaft Stabilizer	Asphalt Distributor(?)
	Multi-Shaft Stabilizer	Aggregate Distributor(?)
	Windrow Mixer	Windrow Sizer (?)
	Mixer Paver	Bucket Loader(?)
		Windrow Elevator(?)
Finishing & Laydown	Motor Grader	Bucket Loader(?)
	Multi-Shaft Stabilizer	Windrow Elevator(?)
	Mixer Paver	
	Asphalt Paver	
Compaction	Pneumatic Tired	
	Steel Wheel	
	Vibratory	
	Sheepsfoot	
Shaping & Trimming	Motor Grader	Haul Truck(?)
	Subgrade Trimmer	

The choice of crushing and pulverization equipment is a function of the size of ripped material, the material integrity, the origin or type of material and the desired final gradation of the salvaged material. Rollers are normally used in combination with other crushing equipment to perform intermediate size reduction. Hammermills are usually required on plant mixed materials that are placed in lifts greater than 2 inches in thickness, although some large single shaft stabilizers may be used. Single shaft and multi-shaft stabilizers may be used to crush relatively thin pavements without initial loosening of the pavement. Certain chemicals may be used in conjunction with any of the crushing methods listed to aid in crushing the pavements.

The choice of mixing equipment is dependent on the type of binder to be added, the type of recycled pavement that is to be constructed and the degree of quality control of the recycled mix that is required. A motor grader is normally chosen as a supplemental blending tool, although it may be used as a primary mixing tool for recycled materials utilizing emulsions or cutbacks. Single shaft stabilizers may be used to add, mix and disperse liquid asphalt cements, although these machines are normally used to add either emulsions or cutbacks. Additional mixing equipment may be required for material aeration. An asphalt distributor may be required if the mixer chosen does not have an integral additive system. An aggregate distributor may be needed if new aggregate is to be incorporated in the recycled mixture. A windrow former and/or sizer is required if the material is to be mixed using a windrow mixer.

The use of an asphalt paver or mixer-paver to place the recycled materials requires auxiliary equipment (bucket loader or windrow elevator) to pick up the recycled material and place it in the finishing machine.

The choice of compaction equipment is dependent on the type of binder that is employed in the recycled mixture. Normally, some combination of two or more rollers will be used.

Shaping and trimming may be required if the recycled pavement structure is to receive a high type surface finish. If the trimmed material is not incorporated in the recycled structure or pavement side slopes, auxiliary equipment will be required to pick up and haul away the excess cuttings.

3.2 Evaluation of Anticipated Recycling System Performance

The specific recycling system selected for rehabilitation or reconstruction should be evaluated for anticipated performance. The major areas of performance that should be investigated are:

1. Production
2. Cost
3. Energy Consumption

3.2.1 Production

The recycling system rate of production is an important evaluator of system performance. The system production rate controls the time required to accomplish the recycling operations, and also influences a major portion of the total recycling costs.

When calculating production rates, care must be taken to properly define the type of production that is being derived. Peak rate of production only accounts for the net working time associated with the process operation, while average rate of production includes not only net working time, but also normal delays, as well as labor and machinery inefficiencies. Average production should be used for recycling system evaluation for it more effectively models actual project rates of production.

Normally, equipment and labor inefficiencies are taken into account by the use of efficiency hours or job efficiency factors. These factors are used to derate the peak rate of production to average rate of production. The normal range of these factors is from 60 to 90%, or from 40 to 55 minutes per hour, depending on actual job conditions and the types of labor and machinery used.

Hot surface recycling production is normally calculated and measured in square yards/hour. The forward working speed of the hot recycling unit, as well as the processing width, determines the rate of hot surface recycling production. Since heater-planing and heater-scarification is limited to removing 3/4 inch (or less) of material, the thickness of the material processed does not usually enter into the production calculations. Normally, only planing or scarifying rates of production (surface area/unit of time) are calculated. Major factors that will affect hot surface recycling production are:

1. Climatic conditions - temperature, wind velocity, surface moisture
2. Amount of overlap of successive passes
3. Supply of new material for some heater-scarification processes

Hot milling production, because of greater depth of removal, should be calculated or measured using volume rates of production (usually square yard-inches per hour or cubic yards per hour). Depth per milling pass, as well as the number of passes required will influence hot milling production. See Section 7.2 (V.II) for actual production rates achieved on hot surface recycling projects.

Cold surface recycling production is calculated or measured using a milling rate of production (square yards/hour) or a volume rate of produc-

tion (square yard-inches/hour, cubic yards/hour, or tons/hour). The rate of production is calculated based on forward milling speed, width of milling operation and, in some cases, depth of removal. Many factors influence the cold milling rate of production. These factors are:

1. Milling Power - Horsepower/inch of cutting width
2. Full Width versus partial width milling
3. Full depth versus partial depth milling
4. Pavement aggregate and associated tooth wear
5. Coordination of spoil hauling units and the cold miller*

See Section 7.3.2 (V.II) for detailed background information and actual rates of cold surface production achieved on surface recycling projects.

Central plant recycling production is normally measured in tons per hour. The central plant recycling system production is influenced by the production of three system components: asphalt plant; haul trucks; and paving operations. The component that most influences recycling production is the asphalt plant. Even though most central plant recycling is accomplished using conventional (but modified) batch plants or drum mixers, the manufacture's original rated production for the plant must be derated to reflect the recycling requirements and plant modifications. The need to recycle salvaged pavement materials with minimal emissions has the greatest effect on asphalt plant production. The modifications that are incorporated in drum mixers to prevent hydrocarbon emissions, as well as the high temperature limits associated with batch plant operations, lead to a substantial reduction in the original plant's production capability. Other factors that should be taken into account when analyzing central plant recycling

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*An excellent analysis of the many factors and their effects on cold milling production can be found in a FHWA study "Milling Equipment Production Efficiency Study on Pavement Planing Equipment" [113].

production are:

1. Salvage asphalt/virgin aggregate blending ratios
2. Required discharge temperatures
3. Moisture added to the cold feed material to aid in controlling emissions

See Section 8.4 (V.II) for further amplification of central plant recycling production.

The transportation of both the salvaged pavement material and the recycled material can also influence central plant recycling system production. Normally, sufficient salvaged material is transported, processed and stockpiled in advance of the actual recycling operation so that haul units are not a controlling factor on the input side of the system. However, the proper balancing of trucks with the central plant recycling operations and the paving operations is crucial. The proper number of trucks should be selected so that paving production, hauling production and recycled mixing production are in balance. Many factors affect the haul unit production, but the major one is the distance that the plant is located from the project. Truck cycle times must be accurately calculated if the proper number of trucks needed to balance the system production is to be chosen.

Usually the paving operation can be varied to meet the central plant's and the haul truck's rate of production. The most important factor is to chose the proper forward speed of the asphalt finisher so that material is always available to the paver, thus preventing stopping and starting of paving operations. Since the temperature of the recycled mix is normally lower than conventional mixes, the choice of and the use of compaction equipment will also influence system production.

In-place recycling system production, more than any other recycling method, is dependent on the component process rates of production. Although individual component production rates can be readily calculated, the total system rate of production is greatly influenced by the sequencing and overlapping of component processes. Each component process rate of production (except the first) is dependent on the preceding process operation. Thus, evaluation of total system production can be difficult.

Ripping production (normally measured in cubic yards/hour) can be calculated based upon the forward (and reverse) working speed of the ripper, as well as spacing between ripping passes. Factors that affect ripping production are:

1. Pavement ripability*
2. Tractor or grader power and gross weight
3. Number of ripper(s) or scarifying teeth employed

See Section 9.4.3.1 (V.II) for full amplification of ripping production.

Crushing and pulverization production is normally calculated and measured in cubic yards/hour. However, it is important that the type of cubic yards, in-place or loose cubic yards, be properly identified and consistently used in the production calculation process. The variables that control production are: the processing speed; the width or depth or the amount of windrowed material processed per pass; and the number of passes required. The desired final gradation, as well as the material quality, influences the number of crushing passes needed. The wearability of stabilizer teeth and hammermill hammers will also have an effect on crushing production. See Section 9.4.3.2 (V.II).

*See Caterpillar Handbook of Ripping [82] for techniques to relate pavement ripability with production by means of sesmic velocity.

Mixing production is normally calculated and measured in cubic yards/hour or square yards/hour (for a given mixing depth). Mixing speed, width and depth or windrow size and the number of mixing passes required will determine the basic rate of production. The type of binder added, the need for new or salvaged aggregate and aeration requirements will have a large effect on mixing production. See Section 9.4.3.3 (V.II).

Compaction production is related to recycled material mixing and lay-down production and is usually measured in square yards/hour. Working speed, compaction width, amount of overlap and number of passes are the basic parameters used to calculate production. The type of recycled material, the thickness of the recycled layer and whether vibratory compaction is used will influence compaction production.

The total in-place system production can be calculated from the component rates of production. More importantly, however, is the time required by each individual system component to accomplish its particular process operation.

3.2.2 Cost

The cost of producing the recycled pavement is another important evaluator of system performance. All costs associated with recycling should be identified and estimated. Recycling project costs can be classified into one of the following categories: materials; labor; equipment; overhead and profit. Profit and some overhead costs (general overhead) while important in the bidding process and financial well being of the contractor, will not normally be a part of the recycling performance evaluation. The recycling costs that should be calculated are those direct costs that are related to the recycling operations.

The initial step in the cost estimation process is the determination of the size of the recycled project. Normally, the size of the project should be measured in square yards, square yards-inches, cubic yards or tons.

The cost of all new materials to be incorporated in the recycled product should be identified and estimated. Transportation and handling charges should be included in the material cost estimate. Typical new materials that may be required for recycling operations are:

New binder and/or rejuvenating material

New aggregate

New hot mix asphalt concrete (required for some heater-scarification processes)

Liquid asphalt for tack coats and prime coats

Surface treatments and virgin overlay materials

The appropriate quantities of these materials and their respective unit prices should be estimated and used to determine total material costs.

The cost of all labor associated with the recycling project should be identified and estimated. However, a majority of the labor needed for recycling operations is associated with equipment operators, truck drivers and other equipment support people (oilers, cold miller ground men, paver screed operators, etc.). This type of labor cost is normally included as part of the equipment cost. Project supervision and engineering staff is normally included in the project overhead, which may or may not be used in the system cost evaluation.

The major cost associated with recycling operations is equipment costs. Recycling is an equipment intensive process and, as such, equipment costs ($/HR) and production rates (CY/HR, TPH, etc.) are an extremely important part of calculating total recycling system cost.

Equipment used in the recycling process may be either rented, leased or contractor owned. Estimating equipment costs when the machinery is rented or leased is quite easy, for the lessor determines the hourly charge. Normally, deductions from the rental rate will be made if the contractor provides routine maintenance and servicing. Fuel costs and operator's wages must be added to the basic rental rate.

When the equipment is contractor owned or if it is to be purchased, the equipment owning and operating costs (O and O costs) should be calculated. The components of the O and O costs, as well as a suggested procedure for calculating O and O costs, are listed in Table 3-4. See Section 9.6.1 (V.II) for the cost of purchasing selected recycling equipment.

Equipment depreciation is a major part of owning costs. In order to calculate the hourly depreciation charge, a depreciation period or service life must be chosen. A useful guide to selecting an appropriate depreciation period can be found in numerous trade association publications. (e.g. AASHTO [27]). The normal service life for most mobile recycling equipment ranges from 5,000 to 10,000 hours.

The yearly cost of taxes, insurance, interest (cost of borrowing or lost investment opportunity) and storage are usually calculated as a percentage (10 to 20%) of the average yearly investment. The cost of tires should be deducted from the ownership costs and included in the operating cost.

An estimate of general repair cost is usually based upon past experience with the specific type of machine. General repair costs are normally calculated as a percentage of the hourly depreciation cost.

The cost of fuel is based upon the hourly rate of fuel consumption. See Sections 7.2, 7.3.2.4, 8.5.2 and 9.7 (V.II) for reported fuel consumption rates. If no historical data is available, fuel consumption can be

Table 3-4 Owning and Operating Cost Calculation

OWNING COSTS

- Depreciation
  - Purchase Price (inc. all options)
  - Freight, Assembly, Inspection
    - Total Delivered Price
    - less Tire Cost
    - less Salvage Value
    - Total Deductions
  - Depreciable Amount
    - Service Life - hours
    - Depreciation Method
- Hourly Depreciation Charge
- Taxes, Insurance, Interest, Storage (Yearly Cost ÷ Hours/Year

TOTAL OWNING COST - $/hr

OPERATING COSTS

- Tire Cost - Tire Cost ÷ Tire Life (hr)
- Tire Repair Cost
- General Repairs - Parts & Labor
- Fuel Cost -gallons per hour X $/gallon
- Service Cost - Oil, Lube, Filters
- Hydraulic System - Fluid & Filters
- Fast Wear Items - Installed cost ÷ Service Life (hr)
- Operator

TOTAL OPERATING COST - $/hr

calculated based on the machine's brake horsepower rating and duty cycle. See Section 9.7 (V.II).

A major operating cost for most recycling equipment is the replacement of fast wear items such as: milling teeth, hammers, stabilizer teeth, pugmill liners and paddles, cutting blades, wing blades and runners. The hourly cost of these items is calculated based upon the service life of these parts. See Section 9.5 (V.II) for some limited service life details.

Equipment owning and operating costs or adjusted rental rates ($/hour), when combined with equipment production (CY/HR, TPH, CY/HR, etc) can be used to estimate the equipment cost of the recycling project in $/CY, $/Ton or $/SY.

The total cost of the recycling project (materials, labor and equipment) should be calculated. A unit cost for the entire project can be calculated by dividing the total cost of the project by the project size. See Sections 7.2.3.3, 7.3.2.3, 8.5.3 and 9.6 (V.II) for typical recycling project unit costs.

3.2.3 Energy

The final evaluator of recycling system performance is energy consumption. All energy demands associated with the production of the recycled product should be identified. Energy required to manufacture and transport new materials used in the recycled products should be calculated (see Section 1.4.2). The fuel required to operate primary process and support equipment should be estimated. See Sections 7.2, 7.3.2.4, 8.5.2 and 9.7 (V.II). The amount of energy consumed in the recycling process should be converted into BTU and totaled for the entire project. A total recycling system unit rate of energy consumption should be calculated. (Total project energy consumption/project size.) See Sections 7.2.3.4, 7.3.2.4, 8.5.2, and

9.7 (V.II).

The recycling system rate of production, unit cost and unit energy consumption can be used to evaluate the performance of the recycling system. These values will also be used to compare the recycling system to an equivalent conventional reconstruction system.

3.3 Comparison of Recycling System and Conventional System

The system selected for recycling should be compared to the conventional rehabilitation alternative identified by the recycling guidelines. A process similar to that used for the formulation and evaluation of the recycling system should be used to generate the conventional rehabilitation system. The same evaluators used to evaluate recycling system performance - production, cost and energy consumption, should be determined for the conventional rehabilitation system. Since a considerable amount of experience exists in this area, no formal procedures will be advanced for calculating conventional system performance evaluators.

The performance of the two systems should be compared. The areas for comparison are:

Cost - initial and life cycle costs

Energy consumption

Environmental consideration

3.3.1 Cost

The area of comparison that is probably of most interest and carries the greatest weight when choosing between two alternative systems, is cost. An economic comparison should be made of the recycling system cost and the conventional system cost. However, the analysis should not be limited to comparing only initial costs. Since these alternatives will have different

lives and will require different maintenance and rehabilitation actions during their life, the alternatives should be compared on a life cycle cost basis.

Life cycle costing allows the total expenditures for initial rehabilitation or reconstruction and all maintenance actions taken during the life of the pavement to be converted to an equivalent annual cost (EAC). Thus, alternative rehabilitation systems can be compared on an equivalent annual cost basis even though each alternative has a different expected life.

The procedure for calculating the equivalent annual cost involves selecting: 1. an analysis period; 2. choosing an interest rate or discount rate; 3. determining unit costs for future maintenance actions; and 4. determining the timing of future maintenance actions.

The choice of the analysis period is very important. Normally, the analysis period will be related to the useful life of the pavement. Many factors, such as forecast traffic volumes, future operating conditions and obsolescence enter into the selection of the useful life and make the choice a judgmental decision. Twenty years will be selected as the analysis period for this analysis of rehabilitation alternatives.

The interest rate or discount rate to be used in the analysis is related to the cost of borrowing money in the private and public sectors of the money market, as well as the risk and uncertainty associated with the investment. A reasonable range of interest rates for public works (however, greatly influenced by current economic conditions) might be 8 to 10 percent. Data for interest rates of 8 and 10% is provided for this analysis.

The initial pavement rehabilitation or reconstruction unit cost, as well as required future maintenance unit costs, should be determined. All

cost should be expressed in terms of the same unit (normally SY), and the future maintenance cost should be in terms of present day costs (no correction for inflation is used).

Finally, the timing of the future maintenance operations should be determined. Routine maintenance (eg. crack sealing, etc.) can be considered to occur periodically throughout the analysis period for either rehabilitation alternative. However, the expected service life of the initial rehabilitation operation will vary according to the method selected for pavement rehabilitation. At the end of this service life, heavy maintenance or reconstruction will be required to once again rehabilitate the pavement. Service life data for recycling alternatives is quite limited. A review of the recycling literature provides some insight (which should be reinforced with actual performance data) into the choice of a recycling system service life. In general, the service life of recycled materials can be considered to be:

Surface Recycling - 4 to 8 years

Central Plant recycling - 10 to 20 years

In-place Recycling - 10 to 15 years

Local experience with conventional rehabilitation methods should be used to determine the conventional system's service life.

The mechanics of calculating the equivalent annual cost involves converting all future costs into equivalent present costs, and then expressing the sum of all equivalent present costs in terms of a uniform series of annual costs distributed over the analysis period.

The equivalent present value of future maintenance action is calculated by multiplying each maintenance cost by the appropriate single pavement present worth factor (SPPWF). The SPPWF is obtained from Table 3-5 using

the interest rate (i) selected for the analysis and time (n) in the future when the maintenance action will occur. The present value of all maintenance actions are totaled and the sum is added to the initial rehabilitation or reconstruction cost. The resultant sum is the total present value of all costs to be incurred during the analysis period (n). The equivalent annual cost (EAC) is calculated by multiplying the total present value of all costs by the appropriate capital recovery factor (CRF). The CRF is obtained from Table 3-5 using the analysis interest rate (i) and the analysis period (n). A detailed explanation of the economic analysis procedure is contained in "The Annual cost of Pavements" [72] or Principles of Pavement Design [241].

The equivalent annual cost for each rehabilitation alternative should be computed and compared using this procedure. The alternative with the lower EAC is the economically desirable rehabilitation alternative.

3.3.2 Energy

With the recent awareness and concern in this country of the energy situation, the use of rehabilitation system energy consumption can be an important tool for comparing recycling and conventional rehabilitation alternatives. A unit rate of energy consumption should be calculated for the conventional rehabilitation alternative in much the same manner as it was for the recycling system. Both rates should be based on the same unit measurement. The preferred unit for measuring energy consumption is the BTU/SY of road surface.

Although the selection of the rehabilitation system is not totally dependent on the magnitude and favorable/unfavorable advantage of the difference between the two systems, the difference can play a major part in influencing the choice of a rehabilitation system.

Table 3-5 Compound Interest Factors for 8 and 10 Percent

n	Single Payment Present Worth Factor (SPPWF)		Captial Recovery Factor (CRF)		n
	i = 8%	i = 10%	i = 8%	i = 10%	
1	.926	.909	1.080	1.100	1
2	.857	.826	.561	.576	2
3	.794	.751	.388	.402	3
4	.735	.683	.302	.316	4
5	.681	.621	.250	.264	5
6	.630	.564	.216	.230	6
7	.584	.513	.192	.205	7
8	.540	.466	.174	.187	8
9	.502	.424	.160	.174	9
10	.463	.386	.149	.163	10
11	.429	.350	.140	.154	11
12	.397	.319	.133	.147	12
13	.368	.290	.126	.141	13
14	.340	.263	.121	.136	14
15	.315	.239	.117	.131	15
16	.292	.218	.113	.128	16
17	.270	.198	.110	.125	17
18	.250	.164	.120	.104	18
19	.232	.164	.104	.120	19
20	.214	.149	.102	.118	20

3.3.3 Environment

Finally, a subjective analysis should be made of the environmental ramifications of each alternative. Factors to consider are:

1. Reuse of non-renewable resources
2. Elimination of disposal problems
3. Generation of pollutants (either through recycling or conventional techniques)

Although no quantitative measurement can be assigned to these conditions, each can have an influence on the selection of the appropriate alternative.

The previously outlined procedure of comparing alternatives on the basis of cost (initial and life cycle), energy consumption and environment considerations will allow the prudent selection of an appropriate rehabilitation system based on sound engineering judgment and analysis.

3.4 Pre-Job Analysis

Prior to the start of actual recycling construction operations, the total project should be fully analyzed. The contractor and the owning agency should be aware of the type, quantities and variability of the existing pavement materials that are to be recycled. A determination (if not previously known) should be made of the variability to be expected in producing the recycled product. The pre-job analysis should also identify potential problem areas in advance of actual occurrence during field recycling operations. Identification of these problem areas should reduce or eliminate their effect on actual project performance.

The pre-job analysis should also focus on project management considerations. Such items as scheduling of recycling operations, size of work segments and handling of anticipated traffic should be addressed and analyzed well in advance of the actual construction operations. The intent of the

pre-job analysis is to plan the recycling work so that actual field construction operations are efficiently conducted and a quality product is produced at an economical cost.

3.4.1 Variability

The material test program of the recycling guidelines should provide a reasonable level of information regarding the existing pavement. The program should identify the types and characteristics of the materials in the existing pavements, as well as the variability associated with these materials, as they presently exist in the field. It is very important that the variability of the existing pavement be identified in advance of actual recycling operations. The variability of the thickness of the existing bituminous concrete layers, of the asphalt content of the material to be recycled, and of the gradation of the aggregate, both within the bituminous concrete and the granular base (if it is to be used in the recycling operation), will seriously affect the quality of the final product.

The variability of individual recycled products must also be determined if the recycling operations are to be properly controlled. The variability normally associated with the recycled product can be used to control the quality of the recycling operation. Many tests are normally conducted on materials while they are being constructed. Usually, the tests only indicate whether the process is or is not in compliance with specifications. Normally, corrective actions are taken only after the product is out of compliance with the specifications. With the use of product variability, a trend toward non-compliance can be identified and corrected before the product actually goes out of compliance with the specifications.

A determination of normal or expected product variation should be made if field tests are to be used to properly control recycling operations.

Much has been written regarding the variation associated with conventional asphalt construction procedures [44,77,241]. However, very little information has been compiled regarding various recycled product or recycle processing variation. Thus, before the actual recycling can be controlled, an analysis of the variability to be expected during recycling must be conducted. This poses a problem, for the operations will have to be sampled and variability measured before any operation control can be developed. In some cases, data from conventional asphalt construction practices may be used to estimate recycling variability [77,241]. In other cases, recycling operations are different enough from conventional methods that a new determination of variability must be made.

An adequate number of random samples of the recycled product should be obtained and tested to properly evaluate recycling operation variability. Data from at least 20 to 25 samples should be collected. The location of the sampling points should be randomly selected. The statistics that should be determined for each process evaluated are the average ($\overline{X}$) of the test measurements, the range (R) of the test measurements and the standard deviation (σ) of the test measurements.

Recycling operations that should be investigated for product variability are: crushing operations; mixing operations; and compaction operations. The test variable that is normally used to control the crushing process is the percent of material passing (or retained) on a given sieve size. The amount of material greater than the maximum allowable size is of particular importance, as is the amount of material passing the number 200 sieve. The statistics ($\overline{X}$, R and σ) associated with each crushing method employed should be determined to evaluate normal crushing variability.

The test variables that are normally used to control the mixing process are: the amount of new binder added, the amount of rejuvenating material added and the amount of new or salvaged aggregate added. Normal process statistics should be determined for each of these test variables. Obviously, different forms of recycling will result in vastly different mixing variation statistics. The amount of asphalt cement and/or rejuvenator added to the recycled product is the most critical operation in the recycling process. The variability of this operation should be carefully determined.

Finally, the variability of the compaction operation should be determined. Compaction is normally measured in terms of percent of optimal compaction or pounds per cubic foot. Depending upon the type of recycled material produced and the method of achieving compaction, the average, range and standard deviation of the normal compaction process should be determined.

3.4.2 Control Charts

The control chart is a tool that can be used to show cumulative trends in recycling operations, as well as identifying times when the operation is being conducted outside of acceptable performance standards. The control chart provides a means to anticipate and correct causes that tend to promote the production of an unacceptable product.*

The use of the control charts for recycling operations will usually forewarn the contractor and the owning agency that undesirable trends may be developing and help to decide when to take corrective action, and when not to take corrective action. Although large changes in the process can be

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*An excellent discussion regarding the construction and use of control charts is contained in <u>Quality Assurance in Highway Construction</u> published by the Research and Development Office - Bureau of Public Roads, 1969.

easily detected, successive small changes are not easy to detect. The control chart will highlight these trends and allow the process to be returned to proper control.

3.4.3 Potential Problem Areas

An important part of the pre-job analysis is an assessment of potential recycling problems. An intuitive process, based on past experience, is used to assess potential problem areas for conventional rehabilitation alternatives. However, with the general lack of recycling experience possessed by most contractors and highway agencies, some form of additional or supplemental information is needed to properly analyze the initial recycling jobs attempted.

The information contained within Tables 3-6, 3-7 and 3-8 is an attempt to identify (by no means a complete listing) some of the major areas where problems might arise during recycling operations. Problems that might be expected to develop during the recycling operation are listed for each major form of recycling. Corresponding to each problem are one or more appropriate responses or items that should be considered to solve or mitigate the problems. By examining the appropriate table, it is possible to anticipate problems that might be encountered on a specific job and to take appropriate corrective or preventative actions. Even if it is impossible to prevent the problem from occurring, pre-identification will allow the contractor or highway agency to respond quickly with the appropriate corrective measure when the problem does occur.

Some of the problems listed in the tables are dependent on the method or equipment chosen to accomplish the recycling, while others are based upon the manner in which the operation is conducted or how the equipment is operated. In either case, identification of problem areas in advance of ac-

Table 3-6 Surface Recycling Problem Areas

Potential Problem Area	Considerations and Responses
HOT SURFACE RECYCLING	
Proper Heat Penetration	Limit Construction Season, Min. Air Temp.=$50^{o}F$, Insulating Blankets, Multiple Machines
Generation of Emissions	Lower Surface Temperatures
Damage of Roadside Vegitation	Protect Foliage, Spray Foliage
Road Appurtenances	Identify in Advance, Remove or Work Around
Concrete Utility Patches	Identify in Advance, Remove or Work Around
Rejuvenating Agent Application	Adjust Forward Speed &/or Pumping Rate
Lack of Material for Scarifier Screed	Add Extra Hot Mix Asphalt Concrete
Recompaction of Milled Material	Sweep Immediately Following Milling
Congealing of Stockpiled Material	Reuse Milled Material Immediately
COLD SURFACE RECYCLING	
Gradation of Milled Material	Decrease or Increase Milling Speed
Excessive Depth of Removal-Poor Production	Multiple Milling Passes
Generation of Large Chunks or Slabs	Leave Thin Layer of Pavement Over Base
Generation of Dust	Water on Pavement in Advance of Milling
Street Appurtenances	Identify in Advance, Remove or Work Around
Compaction of Cuttings	Sweep Immediately Following Milling
Consolidation of Stockpiled Tailings	Minimum Stockpile Height, Keep Equipment Off Pile

Table 3-7 Central Plant Recycling Problem Areas

Potential Problem Area	Considerations and Responses
	Removal and Crushing
Excess Fines Generated by Milling	Consider in Mix Design, Specify Larger Coarse Aggregate
Contamination of Salvaged Material with Base Fines	Exercise Care in Loading, Assume Some Base Material Will Be Loaded with Salvaged Material (1-2 inches, or 10-15%)
Oversize Crusher Feed Materials	Reduce to Smaller Size in Field
Crushing Difficulties with High Salvaged Material Temperatures	Water on Crusher Feed
Screening of Patch or Seal Coat Material	Identify In Advance, Eliminate From Crusher Feed
Generation of Dust - Crushing Operation	Water on Crusher Feed
Stockpile (Crushed Material) Congealing	Immediate Use, Keep Equipment Off, Coordinate Mixing and Crushing
Stockpile (Crushed Material) Segregation	Limit Stockpile Height to 10 ft., Place in 2 ft. Lifts, Use Two Stockpiles - Fine and Coarse
	Mixing
Bridging of Salvaged Material in Cold Feed Bins	Bin Vibrators
Excess Moisture in Salvaged Material Cold Feed	Use Salvaged Material Immediately, Cover Stockpile
Ignition of Excess Small Fines	Limit Fines, Water on Cold Feed
Plugging of Batch Plant Screens	Remove Screens
	Placement of Recycled Material
"Fluffier" Than Normal Mix	Place Thicker Lift of Uncompacted Material
Low Mat Temperature & Rapid Heat Loss	Place Thicker Lifts (3 in.), Breakdown Rolling Immediately Behind Payer

Table 3-8 In-Place Recycling Problem Areas

Potential Problem Area	Considerations and Responses
Ripping and Crushing	
Ripped Pieces Too Big	Reduce Space Between Ripping Passes, Run Roller Over Material
Excess Fines in Salvaged Material	Limit Depth of Ripping to Pavement Thickness, Eliminate Traffic
Crushing Operation Inefficient	Feed Pieces Too Large, Reduce Feed Size
Generation of Excess Fines - Hammermill	Assume Twice Asphalt Thickness Will Be Processed
Stabilizer Shear Protection - Cobbles	Remove In Advance of Crushing
Excessive Volume of Material to Crush	Multiple Windrows
Chemical Reduction Slow Acting	Min. Air Temperature - 70^{o}F, Min Ground Temperature -60^{o}F, Keep Material Saturated
Generation of Dust, Excessive Tooth Wear	Add Moisture to Ripped Material
Excess Moisture in Ripped & Crushed Mat.	Limit Operations to One Day's Production
Mixing	
Excess Material To Be Properly Mixed	Multiple Mixing Lifts
Large Amount of Binder To Be Added	Multiple Applications, Limit To 1% per Pass, Mixing Between
Large Amount of New Aggregate To Be Added	Multiple Applications, Mixing Between Applications
Excess Moisture in Salvaged Material	Aerate Prior to Mixing, Max. Moisture 3% (Emulsions), 7% (AC)
Too Little Moisture In Salvaged Material	Add Water, Min. Moisture 2%(Emulsions), 4% (AC)
Inadequate Asphalt Dispersion	Additional Mixing Passes
Low Temperature Mixing	Limit Construction Season, Min. Air Temperature - 40^{o}F
Laydown, Compaction & Trimming	
Improper Roadway Crown	Use Paver Rather Than Blade
Excess Moisture in Mix-Improper Compaction	Aerate, Maximum Moisture - 3 to 4%
Shoving of Recycled Mix	Excess Moisture in Mix, Aerate (Leads to Strength Reduction)
Overcuring - Inadequate Compaction	Compact Within Reasonable Time
Undercompaction	No Gain In Strength With Curing - 95% Min. Compaction
Tire Tracks In Compacted Mix	Steel Wheel Roller For Breakdown Rather Than Pneumatic Tired
Curing	Delay Overlay 7 to 14 Days After Compaction

tual construction will allow an intelligent decision to be made as to how the project should be planned and the recycling operations conducted. After some experience with recycling asphalt pavements, this process will become as instinctive for recycling work as it is for conventional work.

3.4.4 Project Management Decisions

Finally, the pre-job analysis should focus on project management decisions that can affect the manner in which the recycling is accomplished. The scheduling of recycling activities, the size of the project segments to be processed at one time and the handling of traffic during recycling are all interrelated factors that should be planned in advance of actual recycling operations.

The scheduling of recycling work activities involves two different scheduling concepts. One scheduling consideration involves the choice of the actual time of the year when the recycling operation can take place. All recycling methods, with the exception of cold milling, require minimum climatic conditions (usually temperature and the absence of moisture) for successful process execution. This is not really any different than seasonal restrictions normally placed on conventional methods. In general, those climatic restrictions placed on conventional construction methods would be an appropriate guide for the seasonal restrictions for an equivalent recycling method, (e.g. hot mix restrictions for central plant recycling; road mix or stabilized base restrictions for in-place recycling).

The other scheduling consideration is the coordination of the individual recycling operations and all support processes that make up the recycling system. The interdependence of individual recycling operations should be thoroughly understood. Requisite predecessor and successor operations, as well as concurrent support processes, should be identified for each recy-

cling operation. These operations and processes should be planned and scheduled so that the project runs smoothly without any avoidable disruptions.

The operations and processes that should be planned and scheduled for hot surface recycling are such items as:

1. Sweeping and other street preparation activities
2. Location and/or adjustment of street appurtenances
3. Timely supply of hot mix for heater-scarification and overlay processes
4. Compaction at the proper time
5. Coordination of pickup and transportation of planed or milled material

The items that should be planned and scheduled for cold surface recycling are:

1. Water for dust suppression
2. Location and/or adjustment of street appurtenances
3. Regularly scheduled versus actual wear replacement of milling teeth
4. Coordination of pickup and transportation of milling tailings
5. Street sweeping and overlay operations

The scheduling considerations for central plant recycling are:

1. Coordination of removal and crushing operations
2. Coordination of crushing and mixing operations
3. Timely supply of uncoated aggregate (salvaged or virgin) for mixing operations
4. Base preparation and roadway improvements completed before recycle mixture laydown
5. Matching of mixing, laydown and compaction production

6. Coordination of haul units for both initial salvaging operations and final recycled product

The scheduling considerations for in-place recycling are:

1. Coordination of ripping and crushing operations with mixing operations
2. Timely supply of water for mixing and/or crushing
3. Timely supply of binder for mixing
4. Timely supply of new aggregate for mixing
5. Proper timing of compaction operations
6. Coordination of recycled material curing with overlay operations

All of these scheduling considerations, as well as many operations peculiar to the specific recycling project, must be coordinated for a successful recycling job.

Prior to the start of actual recycling operations, a decision regarding the physical size of the work segments should be made. This decision is closely related to traffic handling considerations. Basically, the decision must be made whether to totally exclude traffic from the construction area or to conduct the recycling operations "under traffic". Total exclusion of traffic allows the greatest flexibility in choosing the size of work segments. The work segments can be selected to optimize recycling system performance. However, in many cases, the choice of excluding traffic from the construction area is not allowed. Therefore, the choice of work segment size must not only consider efficiency of recycling operations, but also compatability of recycling operations with traffic.

The choice of segment size is also highly dependent on the method of recycling employed. Hot and cold surface recycling normally processes the pavement one lane at a time. Since few support activities or auxiliary

operations are required, only the immediate area in front of and behind the recycling operations is affected. Central plant and in-place recycling depend on several highly interrelated recycling operations which normally require that the recycling operations be limited to one or two sections at a time. Normally, the size of the segments selected for central plant recycling is fairly large, due to the need to process and recycle the salvaged material away from the construction site. The size of in-place recycling segments is usually much smaller. The normal size of in-place recycling segments is limited to approximately one day's mixing production, (mainly attributable to atmospheric moisture conditions).

The environmental location of the pavement will also influence the choice of segment size. The segment size for recycling work in urban areas is normally much smaller (several blocks) than the size for rural recycling operations.

Finally, the maintenance of traffic should be carefully planned. Handling of traffic while recycling operations are being conducted is a major component of total recycling system cost. Not only must people and equipment be obtained to handle the traffic, but the traffic control must be coordinated with the recycling operations.

Control of traffic during surface recycling operations is not much of a problem because the pavement is normally recycled one lane at a time, and only a relatively short segment of the lane is affected. Traffic is normally diverted to an adjacent lane or shoulder in the immediate area of the recycling activities. Immediately after the recycling process is completed, traffic may be allowed back on the recycled surface.

Handling of traffic during central plant operations poses many problems. Ideally, traffic should be eliminated from the construction area.

Practically, the traffic is normally detoured or routed onto adjacent lanes. If the pavement that is being recycled is a divided highway, two way traffic can be established on one side of the highway while recycling activities take place on the other side. Two lane highways that are recycled can use the shoulder to carry one lane of traffic. Alternatively, the lane not being recycled may be used to carry, alternately, both directions of traffic. Since central plant recycling operations normally require that the pavement be reconstructed over a moderate to long period of time, physical barriers separating construction activities and traffic may be required.

In-place recycling, because of the nature of the ripping and crushing operations, is normally conducted as a full width operation, recycling all traffic lanes at a time. However, since rain has an adverse effect on salvaging and mixing operations, the work segments are usually limited to a relatively short length (1000 to 2000 feet or several city blocks). A low volume of slow speed traffic may be allowed on the pavement while recycling operations are being conducted. However, problems should be anticipated. Crushed material should be bladed and roughly graded before traffic is allowed on the material. Speeds should be held down to prevent loose material from being kicked up. Problems should be anticipated with traffic bringing excess fines into the crushed materials. In some cases, where the crushed material is to be left open to traffic at night, some compactive effort should be applied to the crushed material at the end of the work day. Traffic can be allowed on the recycled material after mixing and initial compaction is completed. In fact, some traffic on the structure during this curing period (before an overlay or surface treatment is applied) may be beneficial. However, speeds should be held down to prevent surface raveling.

3.5 Specifications

Finally, a set of specifications should be developed to insure that the recycling work is properly executed and a quality product is achieved. Guide specifications have been formulated for specific recycling methods.* The guide specifications are intended to supplement and/or to provide input so that existing transportation agency specifications can be revised. Guide specifications are provided for the following recycling methods:

*The guide specifications were synthesized by the writer utilizing numerous recycling specifications written by equipment manufacturers, trade associations and transportation agencies.

1. Heater-Planer and Hot Milling

2. Heater-Scarification

3. Cold Milling

4. Central Plant Recycling

5. In-place Recycling

3.5.1 Guide Specifications for Heater-Planing and Hot Milling

Description: This item shall consist of planing or leveling an existing pavement by removing existing irregularities until a smooth surface is produced. If indicated, the pavement shall be cut to a predetermined grade or cross-section as indicated in the plans and specifications or as directed by the Engineer. The planed and finished surface shall be free from gouges, grooves, ridges, sooting, oil film and other imperfections of workmanship. Operations shall be planned so as to be safe as possible for persons and properties adjacent to the work. The route (will) (will not) be kept open to traffic during construction.

Materials: No additional materials will be utilized.

Equipment: The heater-planer or hot milling machine shall be of the type specifically designed and built exclusively for planing or milling a pavement. The equipment shall have a record of successful operation on work comparable to that proposed to be done under this contract. The equipment shall be self-propelled and have in combination the means for heating and planing or milling the surface to a predetermined grade. The machine shall be capable of blading the cuttings into one windrow beneath the machine from which they may be picked up. The equipment shall meet the standards of the applicable State and Federal air pollution control laws.

Heater-planer units shall consist of burners of a type specially designed for the purpose and capable of producing a minimum of 10 million BTUh. The heat shall be applied under an enclosure or shielded hood. The heating and cutting width of the machine shall be the same and shall not be less than eight feet. The machine shall be capable of covering a minimum of 1500 square yards per hour while heating and removing a minimum of 1/4 to 1/2 inch of the existing pavement per pass.

Hot milling units shall consist of a cutting drum with replaceable bits, teeth or edges. Drum lacing patterns may permit a grooved or smooth surface finish, as selected by the Engineer. The machine shall be capable of operating at speeds from 5 to 50 feet per minute and designed to cut 0 to 3 inches deep to predetermined grade in a single pass.

Construction: The temperature at which the work is performed, the nature and condition of the equipment, and the manner of performing the work shall be such that the pavement is not torn, gouged, shoved, broken, oil coated, burned or otherwise injured by planing or milling operations. The surface temperature of the old pavement shall not be heated in excess of 400°F. Sufficient passes, or cuts, shall be made such that all irregularities or high spots are eliminated and that 100% of the surface area has been planed to the desired grade or to the satisfaction of the Engineer. The finished surface shall not vary more than 1/4 of an inch when tested with a ten foot straight edge.

Where the pavement is to be resurfaced, a one inch header shall be cut along the gutter to obviate the necessity of feathering the edge of the new surface.

The contractor shall provide all necessary labor, materials and equipment to load the asphalt and aggregate cuttings into dump trucks supplied and operated by the owner, (alternatively this could be changed to: into sufficient dump trucks supplied by him and hauled to a disposal area designed by the Engineer.) A standardized self-propelled street sweeper should be utilized so that no loose material shall remain on the street at the end of each work period.

The operation shall be conducted so as to prevent damage to trees and shrubs. Parkway trees may be protected from heat damage by individual

shielding and/or water spray, as deemed practical by the Engineer.

Heater-planing and hot milling shall be performed only when the air temperature is above 45°F, as measured in the shade.

Measurement: Asphaltic pavement planing and milling performed and completed to these specifications shall be measured by the Square Yard.

Payment: Payment for planing or milling will be made at the contract unit price per Square Yard. The unit price shall include all labor, equipment, materials, supplies, mobilization, bond and insurance for planing or milling pavement. Price bid per Square Yard (will) (will not) include necessary traffic control.

3.5.2 Guide Specifications for Heater-Scarification

Description: The work shall be part of a multi-step process of asphalt surface rehabilitation that consists of softening the existing flexible pavement with heat and thoroughly stirring or tumbling the mixture; applying an asphalt rejuvenating agent, as required; and placing a surface treatment or overlay, as required. Operations shall be planned so as to be safe as possible for persons and properties adjacent to the work, including the traveling public. The route (will) (will not) be kept open to traffic during construction.

Materials: Recycling Modifier - The asphalt modifier shall be specified by the Engineer prior to the letting of the contract and shall conform to the Contracting Agency's Standard Specifications for Recycling Modifiers.

Asphalt - The type and grade of asphalt cement for the seal coat and/or asphalt concrete shall be specified by the Engineer prior to the letting and shall conform to the Contracting Agency's Standard Specifications for Asphalt Cements.

Aggregates - The type and grade of aggregate for the seal coat and/or asphalt concrete shall be specified by the Engineer prior to the letting and shall conform to the Contracting Agency's Standard Specifications for Aggregates.

Asphalt Concrete - The mix for the asphalt concrete shall be designed and produced in accordance with the Contracting Agency's Standard Specifications for Asphalt Concrete.

Equipment: Heater-Scarifier - The equipment used for heating and scarifying shall be a self-contained, self-propelled unit specifically designed for this purpose. The equipment shall have a record of successful operation on work comparable to that proposed to be done under this contract. The heat-

ing unit shall consist of burners of a type specifically designed for the purpose and capable of producing a minimum of 10 million BTUh. Heat shall be applied under an enclosed or shielded hood. The heating and scarifying width should be the same and shall not be less than eight feet. The scarifying unit shall consist of pressure activated teeth, rakes, or scarifiers capable of scarifying to a minimum depth of 3/4 inch or as specified by the Engineer. The machine shall be capable of heating and scarifying a minimum of 1000 square yards per hour. The equipment shall meet the standards of the State and Federal air pollution control laws. A screed or leveling device shall be provided and shall be capable of distributing the heated and processed material over the width being processed so as to produce a uniform cross-section. The leveling device shall have the capability of windrowing excess material to one side for removal when necessary.

Distributor - The equipment used for applying the rejuvenating agent or asphalt shall conform to the Contracting Agency's Standard Specifications for Bituminous Distributors and shall be capable of applying a continuous and uniform application. The distributor may be an integral part of the heater-scarifier or may be a separate piece of equipment.

Rollers - A smooth tread pneumatic tired roller or steel wheel roller, conforming to the Contracting Agency's Standard Specifications for Rollers should be used to compact heater-scarified mixes. The roller should be in a range of 10 to 12 tons, gross weight.

<u>Construction</u>: Surface Preparation - The pavement surface to be heater-scarified shall be cleaned of trash, debris, earth or other deleterious substances.

Heater-Scarification - The pavement surface shall be evenly heated and remixed to a depth of between .05 to .07 feet (or as specified by the En-

gineer) by a continuously moving heater-scarifier. At least 90% of the aggregate shall be remixed by spinning or tumbling. The surface temperature of the existing pavement shall not exceed 400°F during heating. Heater-scarified material shall have a temperature in a range between 200 to 260°F, measured immediately behind the heater-scarifier. The remixed layer shall be uniformly and evenly heated throughout. No uncontrolled heating, causing differential softening of the upper surface, will be permitted. The asphalt binder shall not be carbonized in excess of .10 percent. When a heater-scarification pass is being made adjacent to a previously placed mat, the longitudinal joint shall extend at least 2 inches into the previously placed mat.

Leveling - Following heater-scarification and prior to overlay installation, the scarified material shall be uniformly distributed to the desired longitudinal and transverse section by the use of a leveling device. The minimum temperature of the material as it leaves the leveling device shall be 175°F.

Application of Recycling Modifier - The application of the recycling modifier (if needed) shall be determined by the Engineer. The recycling modifier may be applied to the existing pavement in advance of heater-scarification. (Note: Alternatively, the recycling modifier may be applied to the heater-scarification material immediately following scarification.) (Note: Alternatively, the recycling modifier may be applied immediately following leveling of the heater-scarified material, but in advance of new material overlay.) The timing, type and amount of recycling modifier shall be determined by the Engineer. Overlapping applications of the recycling modifier or leaking of the distributor spray bar will not be allowed.

Overlay - Closely following and within five minutes after leveling the scarified mat and before the mat temperature drops below 150°F, a uniform layer of new surface course material (if required) shall be applied by a vibratory screed or strike-off assembly in accordance with the Contracting Agency's Standard Specifications for Placement of Wearing Courses. (Note: Alternatively, the new asphalt concrete may be mixed with the old scarified pavement, distributed and leveled utilizing a special type heater-scarifier.) The type and amount of asphalt concrete shall be indicated in the plans and specifications or specified by the Engineer.

Compaction - Immediately following the placement of the new material overlay (if required), the pavement shall be compacted with an approved roller. A minimum of two passes shall be made. Additional passes may be made at the direction of the Engineer. (Note: Where a new material overlay is not used, compaction shall immediately follow the placement and leveling of the heater-scarified material.)

Weather Limitations - Heater-Scarification shall be performed only when the weather is dry and there is no free water on the pavement. Heater-scarification shall be performed only when the air temperature, as measured in the shade, is above 50°F.

Measurement: Asphalt heater-scarification performed and completed to the specifications above shall be measured by the Square Yard, the recycling modifier by the Gallon applied and the bituminous concrete by the Ton applied.

Payment: Unit prices shall include all labor, equipment, materials, supplies, mobilization, bond and insurance to complete each item. Payment for: heating and scarifying will be made at the price bid per Square Yard; recycling modifier will be made at the price bid per Gallon; bituminous concrete

will be made at the price bid per Ton. The price bid (will) (will not) include necessary traffic control.

3.5.3 Guide Specifications for Cold Milling

Description: This item shall consist of improving the profile, cross-slope and surface texture of an existing asphalt concrete pavement and removing excess bituminous material to the depths indicated on the plans and the removal and disposal or stockpiling of the removed materials at the locations designated on the plans or specified by the Engineer. The milled surface shall provide a smooth riding surface free from gouges, continuous grooves, ridges and other surface imperfections of workmanship and shall have a uniform textured appearance. Operations shall be planned so as to be safe as possible for persons and properties adjacent to the work. The route (will) (will not) be kept open to traffic during construction.

Materials: No additional materials will be utilized.

Equipment: The equipment for profiling, texturizing and removing the bituminous surface material shall be a power operated, self-propelled milling machine capable of removing, in one pass, a thickness of asphalt concrete necessary to provide profile, cross-slope and desired texture uniformly across the entire pavement surface. The machine shall be capable of removing a layer of bituminous material 5 feet in width and 3 inches in depth. The equipment shall be capable of accurately establishing profile grades within ±1/8 inch by referencing from either the existing pavement or from an independent grade control and shall have a positive means for controlling cross-slope elevations. The machine shall be capable of variable milling speed up to 50 feet per minute. The equipment shall also have an effective means for removing excess material from the surface and for preventing any dust, resulting from the operation, from escaping into the air. The equipment shall have a record of successful operation on work comparable to that proposed to be done under this contract. The equipment shall meet the stan-

dards of the State and Federal air pollution control laws.

Construction: The bituminous surface shall be removed to the depth, width, grade and cross-section as shown on the plans or as directed by the Engineer. The asphaltic concrete material shall be removed to within 3 inches of curbs, drain castings and utility covers, and the remaining asphaltic concrete material shall be removed by other methods acceptable to the Engineer. The equipment operations shall be confined to one traffic lane, in so far as possible. Transverse faces that are present at the end of a working period shall be tapered in a manner approved by the Engineer to avoid creating a hazard for traffic. Excess material resulting from the operation shall be removed and disposed of as specified in standard specifications. The contractor shall provide all necessary labor, materials and equipment to load the asphalt and aggregate cuttings into dump trucks supplied and operated by the owner. (Note: Alternatively, into sufficient dump trucks supplied by him and hauled to a disposal area designated by the Engineer.) A standard self-propelled street sweeper shall be utilized so that no loose material shall remain on the street at the end of each work period.

Measurement: Asphaltic pavement milling performed and completed according to these specifications will be measured by area in Square Yards for each 2 inch increment removed. Fractional increments of 1 inch or less will be measured by area in Square Yards.

Payment: Payment for milling 1 inch increments shall be made at the contract unit price per Square Yard. Payment for milling 2 inch increments shall be made at the contract unit price per Square Yard. The unit price shall include all labor, equipment, materials, supplies, mobilization, bond and insurance for milling of pavement and loading asphalt and aggregate cuttings into sufficient dump trucks supplied and operated by (owner) (contrac-

tor). The price bid per square yard (will) (will not) include necessary traffic control.

3.5.4 Guide Specifications for Central Plant Recycling

Description: This work shall consist of removing a designated depth of the existing bituminous pavement, hauling to a designated plant site, sizing the removed material and stockpiling the material. The material shall then be processed (hot) in a mixing plant with additional materials (as required) to required temperature. The material shall then be placed and compacted on the prepared roadway base course in reasonably close conformity with the lines, grades, thicknesses and typical cross-sections shown on the plans or established by the Engineer.

Materials: Salvaged Asphaltic Concrete - The salvaged asphaltic concrete shall be processed in such a manner as to provide a reasonably uniform gradation from fine to coarse and to provide a maximum particle size of 1-1/2 inch in the salvaged asphaltic concrete, and/or a maximum size which will assure that no particles in the final recycled bituminous mixture will be retained on a 1 inch sieve. Mixtures containing road tar as the binding agent shall not be permitted. Also, the salvaged asphaltic concrete shall be free of deleterious or objectionable materials.

Salvaged Base Course Aggregate - For aggregate materials salvaged under this contract and used in the recycled mixture only the quality and maximum size provisions of the Contracting Agency's Standard Specifications for Aggregates shall apply. Also, the gradation of the salvaged aggregate material shall be reasonably uniform from fine to coarse.

Virgin Aggregate - The virgin aggregate used in the recycled mixture shall meet the gradation and quality requirements of the Contracting Agency's Standard Specifications for Mineral Aggregates.

Bituminous Materials - The type and grade of asphalt material for the mixture shall be designated by the Engineer and shall conform to the Con-

tracting Agency's Standard Specifications for Bituminous Materials.

Asphalt Modifier - The asphalt modifier shall be what is commonly called a softening agent, flux oil, rejuvenating agent or soft asphalt cement and shall conform the Contracting Agency's Special Specifications for Modifying Agents.

Recycled Mixture - The recycled mixture shall be an intimate mixture of salvaged asphaltic concrete, salvaged base course aggregate (as required), additional bituminous materials and asphalt modifier (as required). The gradation and combination of materials will be specified on the plans and will include an asphalt cement and/or an asphalt modifier. The type and grade will be as specified by the Engineer. The exact proportions of mineral aggregates, salvaged materials, asphalt and asphalt modifier shall be regulated as directed by the Engineer. A job mix formula for the recycled bituminous mixture will be issued by the Engineer. The job mix formula designated by the Engineer shall be within the following tolerances:

Rate of aggregate feed	±5%
Percent aggregate passing the 1/2 inch sieve	±8%
Percent aggregate passing the no. 8 sieve	±6%
Percent aggregate passing the no. 200 sieve	±3%
Bituminous material added	±0.3%
Asphalt modifier added	±0.3%

Equipment: The equipment shall include: 1. one or more asphalt heating and mixing plants designed to produce a uniform recycled mixture within the job mix tolerances; 2. one or more self-propelled pavers capable of spreading the recycled mixture to the thickness and width specified, true to line, grade and crown shown on the plans or specified by the Engineer; 3. enough smooth bed hauling trucks to ensure orderly and continuous paving operations; 4. one or more steel wheel, pneumatic tired or vibratory rollers capable of obtaining the required density and smoothness; 5. hand tools neces-

sary to complete the job. Other equipment may be used in addition to, or in lieu of, the specified equipment when approved by the Engineer.

Mixing Plant - The mixing plant shall be of a type that will produce the required mixture set forth in the contract plans and as directed by the Engineer. Mixing plants may be either the standard weight batching type or the dryer drum type, as long as they are equipped with proper proportioning and weighing mechanisms, satisfactory conveyors, power units, aggregate handling equipment, hot aggregate bins (if required) and pollution control devices. The plant shall be capable of complying with all applicable State and Federal air quality standards.

Construction: Removal of Existing Pavement - The existing bituminous pavement shall be removed to a depth, line and grade as shown on the plans and established by the Engineer. The existing bituminous pavement shall be removed in such a manner as to prevent unnecessary intermixing of underlying materials and damage to underlying pavement courses. The bituminous pavement shall be broken to a size that is convenient to load and haul to a central crushing site.

Crushing and Stockpiling - The bituminous material removed for recycling shall be crushed in a closed cycle system so that 95% of the material shall have a least dimension of 1-1/2 inches. (Note: Existing bituminous pavement materials may be removed by approved cold milling equipment which may obviate the need for further crushing and processing.) The material shall be passed through a 2 inch scalping screen prior to the material being introduced into the mixing plant. During the crushing operation, the coarse aggregate (+ #4 material) and fine aggregate (- #4 material) shall be stockpiled in separate piles. The stockpile area shall be approved by the Engineer and shall be graded and compacted to produce a firm, level base.

Layer placing, stacking conveyors or other approved methods shall be used for stockpiling to prevent coning or segregation of the stockpiled material.

Heating and Mixing - The combination of salvaged base material (if required), virgin aggregate (if required) and crushed salvaged asphaltic pavement shall be introduced into an approved mixer. The bituminous material and asphalt modifier shall be introduced into the mixer through separate metering devices for each material. The mixing operation shall continue at temperatures suitable for mixing until a homogeneous, uniformly coated mixed is achieved. The temperature of the recycled bituminous mixture at the point of discharge from the mixer shall not exceed 300°F. The temperature of the mix at laydown shall not be less than 180°F. The actual mixing temperature shall be adjusted, as directed by the Engineer within the allowable limitations, to facilitate construction conditions. The moisture content of the recycled bituminous mixture at discharge from the mixer shall not exceed 3%.

Spreading, Compaction and Finishing - The recycled mixture shall be spread and compacted in accordance with the Contracting Agency's Standard Specifications for Spreading and Compacting Conventional Asphalt Mixes. Weather and seasonal limitations for conventional asphalt concrete mixes shall apply to recycled mixtures.

General: Samples - At least 21 days prior to the start of production of the recycled mixture, representative samples of the materials to be used shall be submitted by the contractor to the Engineer. Sampling of asphalt materials shall be in accordance with the latest provisions of ASTM Designation D 140. Sampling of aggregates shall be in accordance with the latest provisions of ASTM Designation D 75. Sampling of the recycled asphalt mixture, as required by the Engineer, shall be in accordance with the latest provi-

sions of ASTM Designation D 979.

Testing - The recycled mixture shall be tested for asphalt content in accordance with the latest provisions of ASTM Designation D 2172. The recycled mixture shall be tested for compliance with aggregate grading requirements in accordance with the lastest provisions of ASTM Designation C 136.

Weather - Recycled mixtures shall not be placed when the air temperature is at or below 40°F, nor when the surface on which the mixture is to be placed is wet, nor when other conditions are obviously unsuitable.

Measurement: Salvaged Asphalt Concrete - Removal of existing bituminous pavement and crushed, in stockpile, will be measured by the Ton.

Salvaged Base Course Aggregate - Removal and stockpiling of existing base course aggregate will be measured by the Ton.

Bituminous Material - Bituminous material incorporated in the recycled mix will be measured by the Ton.

Asphalt Modifier - Asphalt Modifier incorporated in the recycled mix will be measured by the Gallon.

Recycled Mixture - Recycled asphaltic concrete will be measured by the number of Tons incorporated in the work.

Payment: The accepted quantities of Salvaged Asphaltic Concrete, Salvaged Base Course Aggregate, Bituminous Material and Asphalt Modifier will be paid for at the contract unit price, which shall be full compensation for removal, hauling, stockpiling and for all labor, tools, equipment and incidentals necessary to complete the work. The accepted quantities of recycled mixture will be paid for at the contract unit price which shall be full compensation for furnishing and hauling virgin aggregate for mixing, for processing, hauling and placing and for all labor and use of equipment, tools and incidentals necessary to complete the work.

3.5.5 Guide Specifications for In-Place Recycling

Description: This work shall consist of scarifying, pulverizing and crushing an existing pavement, adding new aggregate (as required) and bituminous materials (as required), mixing in-place, shaping and compacting the mixture to the lines, grades and dimensions shown on the plans and as directed by the Engineer.

Materials: Bituminous Materials - The bituminous materials shall conform to the requirements of the Contracting Agency's Standard Specifications for Asphalt Emulsions or Cut-Back Asphalts or Asphalt Cements. The Engineer will determine the type and quantity to be added to the recycled mixture. The Engineer will specify the temperature at which the material shall be used.

Virgin Aggregate - The virgin aggregate shall conform to the gradation and quality requirements of the Contracting Agency's Standard Specifications for Mineral Aggregates. The Engineer will determine the size and quantity of mineral aggregate to be added to the recycled mixture.

Salvaged Asphaltic Concrete Material - The material to be treated under this contract shall consist of a mixture of existing asphaltic pavement material and mineral aggregate (as required) underlying the existing pavement. Existing asphaltic pavement shall be processed in such a manner as to provide a reasonably uniform grading from fine to coarse and to provide a maximum particle size of 2 inches. When mineral aggregate underlying the existing pavement is used, all rocks or lumps of material larger than 2-1/2 inches in greatest dimension shall be removed and discarded.

Equipment: As many as necessary of the following named pieces of equipment shall be used to complete the specified work: rippers and scarifiers; pulverization and crushing equipment; rotary mixers or travel plants; motor graders; windrow devices; aggregate spreaders; power brooms or power blower;

self-propelled vibratory or steel wheel tandem and pneumatic tired rollers capable of attaining the required density; a pressure distributor designed and operated to distribute the asphaltic material in a uniform spray without atomization; equipment for heating the asphaltic material; and a water distributor. Other equipment may be used in addition to, or in lieu of, the specified equipment when approved by the Engineer.

Rollers - Rollers shall conform to the requirements of the Contracting Agency's Standard Specifications for Compaction Equipment.

Crushing Equipment - When the use of equipment is specified, the equipment shall be an approved rotary reduction machine having positive depth control adjustments in increments of one-half inch and capable of reducing material which is six inches in thickness. The machine shall be of a type designed by the manufacturer specifically for reduction in size of pavement materials, in-place, and be capable of reducing the pavement materials to the specified size. The machine shall be capable of ensuring consistent size of reduced materials. The machine shall have provisions for controlling the pollutants generated by the size reduction process.

Mixers - Mixers shall be self-propelled and a combination mixer and liquid distributor. The mixing rotor, or rotors, shall have a positive depth control to insure a uniform depth of mixing. The spray bar for distribution of the liquid asphalt shall operate in such a manner that all asphalt will be uniformly applied through the mixer at the time of mixing. The equipment for distributing the bituminous material shall be adjustable and shall measure accurately the amounts of bituminous materials being applied. The asphalt pump shall be a positive displacement-type pump. The mixer shall be equipped in such a manner as to make it possible to accurately check the rate of application of the bitumen at any time. The mixer

shall meet the approval of the Engineer.

Construction: Scarifying and Pulverizing - The existing pavement shall be scarified and uniformly pulverized to a maximum size of 2 inches and to the depth specified on the plans or in the proposal, by one or more passes. The maximum length or width of roadbed to be scarified and pulverized at any one time shall be as directed by the Engineer.

Grading - Excess material not incorporated into the work will become the property of the contractor and shall be disposed of as required by the Contracting Agency's Standard Specifications for Disposal of Surplus Materials or as directed by the Engineer. (Note: Alternatively, the excess material will become the property of the Contracting Agency.) Additional virgin aggregate (as required) shall be placed to attain the plan cross-section and/or gradation. Such application of additional aggregate shall be made immediately after scarification and shall be spread over the surface of the scarified material in a uniform quantity. The additional virgin aggregate shall be thoroughly mixed with the processed material. When a travel plant mixer is to be used, the prepared mixture shall be bladed into one or more windrows suitable for the type of travel mixer. Windrows shall contain sufficient material to produce the required thickness of compacted pavement. When equipment other than a travel mixer is to be used, the processed material shall be shaped to a uniform cross-section and grade.

Mixing with Bituminous Material - The bituminous material shall be added only to that material which can be completely mixed, aerated, dried and compacted in one day. Asphalt shall not be applied when the moisture content of the processed material exceeds 3 percent, unless laboratory tests indicate that a moisture content in excess of 3 percent at the time the asphalt is added will not be harmful, or unless a penetration graded asphalt

cement is to be used. When a penetration graded asphalt cement is to be used, the moisture content of the processed material shall not exceed 7 percent, nor shall the moisture content of the processed material be less than 4 percent. If the machine used for mixing is not equipped to measure and apply the asphalt during the mixing operation, the asphalt shall be applied with an asphalt distributor. When the mixer is equipped to measure and apply the asphalt, the asphalt shall be added through the mixer at the rate and temperature directed by the Engineer. The asphalt shall be applied uniformly at the rate of 0.50 to 0.75 gallons per square yard. The asphalt shall be then initially mixed into the layer. Successive applications of asphalt shall then be applied and mixed in quantities not exceeding 1.0 gallon per square yard. (Note: Penetration graded asphalt cements shall be applied and mixed in one application.) Mixing shall continue until a thoroughly uniform mixture is produced, free from fat spots and excess moisture and/or volatiles are removed in quantity sufficient to provide a compactable mix.

Aeration - Aeration of the mixture shall continue until the mixture is dried to a maximum moisture content of 4.0 percent, based on dry weight. (Note: When penetration graded asphalt cements are utilized, no aeration of the processed material shall be conducted.)

Shaping, Rolling and Compacting - Mixing, shaping and compacting shall be done while the processed material is in a workable state. The processed material shall be so shaped that when compacted it shall be in reasonably close conformity with the lines, grades and cross-sections shown on the plans or established by the Engineer. Initial rolling may be done with a pneumatic tired roller or rollers. The processed mixture shall be compacted to not less than 96 percent of the maximum unit weight of laboratory com-

pacted samples. Rolling shall continue until the entire depth is compacted to the specified density. A determination of the compacted thickness of the layer being placed shall be determined at specified intervals. Areas in which a deficiency of more than 1/2 inch compacted thickness is indicated shall be reworked with added mixed material sufficient to increase the layer to the depth specified. Compaction and final shaping shall occur within 8 hours of the initial application of bituminous materials. (Note: When penetration graded asphalt cement is used, compaction shall be initiated within 15 minutes of initial application of bituminous material, and final shaping shall be completed within 2 hours of the initial application of bituminous material.)

Curing - The compacted material shall be cured to the satisfaction of the Engineer. When approved by the Engineer, the pavement may be opened to traffic prior to placing of the surface. Materials recycled using emulsified asphalts or cut back asphalts as the binder shall cure for a minimum of 1 week (7 calendar days) prior to the application of a surface overlay.

General: Samples - Samples of all materials proposed for use shall be submitted by the contractor to the Engineer for approval. Sampling of asphalt material shall be in accordance with the latest provisions of ASTM Designation D 140. Sampling of aggregates shall be in accordance with the latest provisions of ASTM Designation D 75. Sampling of the recycled asphalt mixture, as required by the Engineer, shall be in accordance with the latest provisions of ASTM Designation D 979.

Testing - The recycled mixture shall be tested for asphalt content in accordance with the latest provisions for ASTM Designation D 2172. The recycled mixture shall be tested for compliance with aggregate grading requirements in accordance with the latest provisions of ASTM Designation C

136. The percentage of water or volatiles in the processed and recycled mixture may be determined using the latest provisions of ASTM Designation D 1461. Alternatively, the moisture content in the processed or recycled mixture may be determined using the latest provisions of AASHTO Designation T 255 (anhydrous denatured alcohol) or AASHTO Designation T 217 (speedy moisture tester).

Weather Limitations - Bituminous material shall not be applied when the air temperature, in the shade, is less than 45 °F, unless otherwise permitted by the Engineer. Work shall be suspended when rain is threatening or the mix is wet.

Measure: Recycled mixture will be measured by the Square Yard of processed material of the required depth, measured in place in its final location, as shown on the plans or otherwise designated by the Engineer. Bituminous material incorporated in the recycled mixture will be measured in Tons. Virgin aggregate (as required) incorporated in the recycled mixture will be measured in Tons.

Payment: The quantities described above shall be paid for at the contract unit price for each item. Payment shall be in full compensation for furnishing, hauling and placing materials for mixing, for rolling and for all labor and use of equipment, tools and incidentals.

CHAPTER FOUR

SAMPLE APPLICATION OF RECYCLING GUIDELINES

A section of Indiana State Road 32 was selected to demonstrate the use of the recycling guidelines developed in this study. The section of highway chosen is located in southern Fountain County and connects State Road 63 on the west with US 41 on the east. The specific portion of the highway examined starts at the junction of SR 32 and US 41 (Steam Corner) and extends 3.7 miles to the west.

State Road 32 is a low volume road that primarily serves local traffic. Major east-west traffic is carried by Interstate 74, located approximately 6 miles to the north. State Road 32 is located in an agricultural area, although within the past several years several coal strip mining operations have opened in the area, generating a significant increase in heavy truck traffic.

4.1 Field Survey Program

The initial step in the recycling guidelines is the Field Survey Program. State Road 32 can be functionally classified as a rural collector highway, due to the type and volume of traffic utilizing the road. The geometry survey of the highway, illustrated in Figure 4-1, identified several problem areas:

1. The travel lanes are very narrow for the functional classification of the highway.
2. The shoulders are very narrow or non-existent. Transition from the

Road INDIANA SR 32 Functional Classification RURAL COLLECTOR

Contract Number ____ Design Traffic 575 ADT

	Measurement or Condition	Comments
Travel Lane		
Lane Width	9 FT.	INADEQUATE - SHOULD BE 11 FT.
Number of Lanes	2	oK
Climbing Lanes	N/A	
Acceleration Lanes	N/A	
Deceleration, Turning, Storage Lanes	N/A	
Shoulders		
Width	NARROW (2 FT. or less) or NON-EXISTENT - NEED 4 FT.	
Median (Divided Highways)	N/A	
Alignment		
Horizontal		
Curvature	2 - 90° SHARP RADIUS TURNS @ 2 3/4 MILE WEST	
Line of Sight	oK	
Right of Way	oK	
Vertical		
Curvature	ABRUPT TRANSITION AT BRIDGES (3) & RR CROSSING	
Line of Sight	oK	
Grade	oK	
Cross-Section		
Crown or Slope (including shoulders)	oK	
Transistions-Edges	ABRUPT (SEVERAL INCHES) IN MOST LOCATIONS	
-Intersections	oK	
Drainage Ditches	NON-FUNCTIONAL OR NON-EXISTENT	
Appurtenances		
Curbs	N/A	
Gutters & Drains	N/A	
Utility Structures	N/A	
Overhead Clearances	N/A	
Safety Structures	N/A	

Figure 4-1 Roadway Geometry Survey

travel lanes to the shoulder is abrupt in most locations.

3. Drainage ditches are either non-existent or non-functional.*

4. Vertical alignment of the highway at several small bridges and a railroad crossing is inadequate with abrupt vertical transitions.

The results of the roadway geometry survey indicate that the cross-section of the highway should be reconstructed with wider travel lanes (minimum of 11 foot**), wider shoulders (minimum of 4 foot**) and functional side drainage ditches.

The Present Serviceability Rating of the highway is 2.5 (see Figure 4-2). The quality of ride provided by the pavement surface was considered to be noticeably inferior to that associated with a new pavement and was considered to be a minimum for high speed traffic (55 mph). Extensive patching of cracks and other surfaces defects, as well as numerous sections of wedge and level courses, were the major contributors to longitudinal uneveness and associated ride discomfort. A PSR rating of 2.5 for this type and classification of road indicates that the pavement is presently serving the traffic in an adequate manner (PSR rating of 2.0 is the minimum value for a road of this classification), but will need a smoothing overlay in the near future.

The skid resistance of the entire section of SR 32 between SR 63 and US 41 was measured and found to have an average skid number (40 mph) of 51.6 (with a standard deviation of 2.2 for 10 ten measurements). The magnitude of the skid number indicates that the frictional skid resistant properties of the pavement surface are adequate and no corrective action is needed at this time.

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*Several times during seasonal periods of high rainfall, excessive flooding and standing water was observed on the highway structure.

**"Geometric Design Guide for Local Roads and Streets," AASHO, 1971.

Section Number	Highway Number
FROM JCT. OF U.S. 41 (STEAM CORNER), WEST 3.7 MILES	INDIANA SR 32

Vehicle	Date	Rater
	3/21/78 a.m. p.m.	ISHC

Rating	
5	
	Very Good
4	
	Good
3	
	Fair 2.5
2	
	Poor
1	
	Very Poor
0	

Influence of behavior elements on present serviceability rating.	No Influence	Minor Influence	Appreciable Influence	Pronounced Influence
Longitudinal Distortion		X		
Transverse Distortion	X			
Cracking			X	
Faulting	X			
Surface Deterioration			X	

Acceptable	
Yes	X
No	
Doubtful	

Figure 4-2 Present Serviceability Rating (after Yoder & Witczak - 241)

The results of the condition survey are illustrated in Figure 4-3. Moderate alligator cracking and some longitudinal cracking in the wheel paths indicate that the structural adequacy of the pavement should be investigated. The alligator cracks have disintegrated into chuckholes in some areas, contributing significantly to ride discomfort, both from the open chuckholes and from those chuckholes that have been patched. Some evidence of corrugations and bumps or humps was also present.

The structural adequacy of the pavement was evaluated by component analysis using the procedure outlined in Section 2.1.1.4. The following steps were used in the analysis:

A Design Subgrade Strength - DSS; CBR = 8

B Calculation of the Effective Thickness - Te:

Component	Material Classification*	Conversion Factor*	Actual** Thickness	Effective Thickness
Subgrade	I	0.00	---	0.00
Gravel Base	III	0.20	4 in.	0.80
Bit. Coated Aggregate	VI	0.70	4 in.	2.80
Surface Seal Coats	V	0.50	1/2 in.	0.25
			Total Effective Thickness - Te =	3.85

* from Table 2-5
** from test pit measurements, see Section 4.2.

C Traffic Analysis: Currently, the highway is rated at 575 ADT.

1. Assume ADT = 600 after the road is reconstructed
2. Assume 25% of the daily traffic is trucks. Note: Table 2-7 indicates that the percentage of trucks should be 15% or less for this type of road. However, with the local strip mining operations, 25% would be more appropriate. Assume 50% of the trucks in the design lane. See Table 2-6. Therefore, the number of

Highway INDIANA SR32 Location WEST OF JCT. U.S. 41
Length 3.7 MILES Width 18'
Pavement Type ASPHALT CONCRETE Date 8/78

Pavement Distress Manifestation	Evaluation		
	Severity	Density	Other Comments
Cracking			
Alligator	MODERATE	FREQUENT	MANY PATCHES SOME DETERIORATION
Longitudinal-wheel track	SLIGHT	FEW	NARROW OPENING
-midlane			
-centerline			
-edge			
Transverse	SLIGHT	FEW	NARROW OPENING
Shrinkage			
Reflection			
Slippage			
Distortion			
Rutting			
Waves			
Bumps or Humps	SLIGHT	FEW-FREQUENT	SOME ASSOCIATED W/ PATCHES
Shoving			
Corrugations	SLIGHT	FEW	WEDGE & LEVEL AREAS
Chuckholes	SLIGHT-MODERATE	FEW-FREQUENT	SOME PATCHED : SOME OPEN
Depressions			
Disintegration			
Chuckholes	SLIGHT-MODERATE	FEW-FREQUENT	SOME PATCHED : SOME OPEN
Raveling			
Weathering - ABRASION	SOME SURFACE ABRASION - DUE TO LUGGED TIRES		
Skid Hazard			
Bleeding			
Polished Aggregate			
Rutting			

Figure 4-3 Simple Condition Survey

trucks in the design lane is 75 (see equation 2-5).

3. Average gross weight of trucks is assumed to be 20,000 pounds. (See Table 2-7).

4. Legal single axle load limit in Indiana is 18 kips.

5. The Initial Traffic Number (ITN) is 19, (see Figure 2-8).

6. No correction is needed for light trucks and automobiles.

7. Assuming a design period (n) of 20 years and an annual growth rate (r) of 3%, the Initial Traffic Number Adjustment Factor (ITNAF) is 1.34 (see equation 2-6).

8. The Design Traffic Number (DTN) is 25.5 (ITN X ITNAF).

D Evaluation of the structural Adequacy of the Pavement: Utilizing Figure 2-10, the required thickness of equivalent hot mix asphalt (Ta) should be 6.5 inches. However, the Effective Thickness (Te) of the present structure is 3.85. Since Ta is greater than Te, the pavement is structurally inadequate and must be strengthened.*

4.2 Historical Records and Material Testing Program

No design or construction records were available for this section of SR 32 because the road was originally constructed by Fountain County at the turn of the century as a gravel surfaced county road. Indiana State Highway Commission records indicate that the asphalt concrete portion of the pavement was stage-constructed over several decades. A review of historical records of the stage construction operations indicates that:

1940 - State of Indiana took over the road from Fountain County, the road surface was gravel.

1958 - A bituminous coated aggregate course, 1-6 inches thick, 20 foot

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*This analysis indicates that a 2.65 inch new material overlay is required.

wide, was applied to the road surface by state forces. Note: Indiana specifications for bituminous coated aggregate require a #11 aggregate gradation (100% passing the 1/2 inch sieve) with a 4 to 6% residual asphalt content, utilizing a cutback asphalt as the binder.

1959 - A surface treatment, full width (18 feet), was applied to the pavement surface by state forces.

1971 - A hot asphalt emulsion surface, type II, was applied full width (18 feet). Note: Indiana specifications for an HAE Type II surface require a #8 aggregate gradation (100% passing the 1 inch sieve) or a #9 aggregate gradation (100% passing the 3/4 inch sieve), with a residual asphalt content of 4.3 to 5.6% utilizing an asphalt emulsion as the binder.

1974 - A sand and squeegee treatment was applied full width.

1975 - A sand and squeegee treatment was applied full width.

Based on the results of the Historical Records Investigation, the nominal aggregate size found in the bituminous material to be salvaged should be 3/4 inch or less, and the asphalt content should range between 4-1/2 to 5-1/2 percent.

A test pit was excavated in the travel lane of the highway in an area where alligator cracking was evident. Bituminous material samples were obtained for laboratory testing and the thicknesses of the existing pavement layers were determined to be:

A. 3/4 inch surface layer

B. 3 to 4 inches of a binder course of bituminous coated aggregate course

C. 4 to 4-1/2 inches of a granular base material

D. Clay-silty subgrade material

Eight cores were obtained at nearly evenly spaced intervals from the 3.7 mile section being investigated. The cored material was tested in the laboratory to characterize the pavement material properties.

The native subgrade material underlying the pavement structure is a Fincastle silt loam.* The material may be classified as a CL or ML under the Unified Soil Classification System, and an A-4 under the AASHTO Soil Classification System. The material is subject to medium frost action. A seasonably high water table (perched) is located less than 2 feet from the surface of the subgrade material.

The base material, which was the original gravel road surface material, can be classified as an Indiana coarse aggregate, gradation number 73, except that the amount of material passing the #200 sieve (15-20%) is outside specification limits (5-10%). The nominal size of the aggregate is 3/4 inch.

The bituminous concrete samples obtained from the test pit had a recovered asphalt content of 4.5 to 5.0%, with an average recovered penetration (77°F) of 38. The gradation of the recovered aggregate fell within the specification limits for an Indiana Type II #8 or #9 gradation, with 97% passing the 3/4 inch sieve. An analysis of the bituminous concrete obtained from the pavement cores showed a similar aggregate gradation. However, the asphalt content was highly variable, averaging 4.2%, with a recovered penetration (77°F) ranging from 14 to 50. The presence of trace amounts of cutback diluents was noted.

*Soil Survey of Fountain County - USDA

4.3 Probable Cause of Distress or Failure

The results of the Field Survey Program, the Historical Records Investigation and the Materials Testing Program were used to determine the probably cause of pavement distress. The distress causing mechanisms that were present and identified by the Field Survey Program, and the associated distress manifestations that should be produced by these defects can be determined from Table 2-8.

Mechanism	Distress Manifestation (see Table 2-9)
1E Water in subgrade-poor drainage	IB,IIF,IIIA
2C Poor drainage of base	IB,IIF,IIIA
3A Fatigue	IA,IC,ID,IIF,IIIA
4A Frost susceptable materials	IB,IC,IIC
4D Low penetration asphalt	IE
6C Excessive loading	IA,IC,ID,IIF,IIIA
6D Heavier than design traffic	IIA,IIG,IVA,IVC

The distress manifestations that were evident and the associated mechanisms producing the distress can be determined from Table 2-9:

Manifestation	Distress Mechanism (see Table 2-8)
IA Alligator Cracking	1A,2A,3A,3B,5B,6C
IC Logitudinal Cracking	1C,1D,1G,2D,3B,3C,4A,5A,5D,5F,6C
ID Transverse Cracking	3B,3C,4G,4H,5L,6C
IIA & IIID Chuckholes	1E,1H,2C,3B,4B,4K,6C
IIID Abrasion	6A

When the results of the two processes are combined, the probable cause of distress can be attributed to:

1. Excessive loading with heavier than design traffic
2. Water in subgrade and poor drainage
3. Frost susceptable material in subgrade and some in the base material

Therefore, any alternative proposed for pavement rehabilitation must treat

these distress mechanisms in order to prevent reoccurrence of the same defects at some time in the future.

4.4 Identification of Rehabilitation Alternatives

The conventional and recycling alternatives that can be utilized to rehabilitate the pavement can be determined by using Tables 2-12, 2-13, 2-14 and 2-15. The general structural condition of the pavement can be classified somewhere between a Case I (all layers structurally unsound) and a Case II (surface layer structurally unsound, but underlying layers structurally sound) with the geometric inadequacies of Case IV. The rehabilitation alternatives identified by these General Structural Cases (see Table 2-12) are:

Conventional	Recycling
Reconstruction	Partial or Full Depth Central Plant
Thick Overlay with Balanced or Unbalanced Widening	In-Place
	Hot or Cold Milling with Overlay

Table 2-13 and the major distress manifestations evident in the pavement (alligator cracking and chuckholes) were utilized to determine the following rehabilitation alternatives (listed in order of treating increasingly severe distress):

Conventional	Recycling
Patching	Heater-Scarification
Overlay	Partial Depth Central Plant
Removal and Reconstruction with Improved Drainage	Full Depth Central Plant
	In-Place

Utilizing Table 2-14 and the distress mechanisms previously identified, the recycling alternatives identified are:

Distress Mechanisms	Recycling Alternative
Subgrade and base defects	Full Depth Central Plant; In-Place
Frost Susceptibility	Partial and Full Depth Central Plant; In-Place
Loading and Heavy Traffic	Hot or Cold Milling with Overlay; Partial and Full Depth Central Plant; In-Place

When the severity of the pavement distress and the need to rebuild and/or change the pavement cross-section is considered, the conventional alternative selected is a thick overlay with reconstruction of drainage structures and widening of the pavement. The recycling alternative selected is either central plant or in-place recycling.

The choice between central plant and in-place recycling can be made utilizing Table 2-15, Other Factors. The factors that are different for the two recycling alternatives and that influence the choice are:

Climatic Effect - Favors central plant over in-place recycling

Project Size - Favors in-place over central plant because of the relatively small size (40,000 sy) of the job.

Environmental Standards - Favors in-place recycling over central plant because of the presence of diluents in the salvaged material and the low level of pollutants generated by in-place.

The recycling rehabilitation alternative identified by these guidelines is in-place recycling. In-place recycling should be used to produce a stabilized base layer that will probably need a new material overlay for structural, wearing and waterproofing reasons.

4.5 Mix Design

The gyratory compactor and the Hveem stabilometer were used to design the recycled asphalt concrete mixture, (see Appendix D (V.II)). Several different binder types were investigated: AC 2.5; MC 3000; AE 150; and AE 90. The AC 2.5 produced the recycled mix with the highest Hveem resistance value, although the mixture utilizing the MC 3000 had a Hveem resistance only slightly less. However, both materials had to be heated in order to properly disperse the new binder in the recycled mixture, while the two emulsions, the AE 150 and AE 90, required no additional heating. However, the emulsions required an extended curing period, while the AC 2.5 required no curing and the MC 3000 required a relatively short curing period. The emulsions coated the recycled material much better than did the asphalt cement. The AE 150 was selected as the new binder in the recycled mix on the basis of these preliminary tests, the requirements of Indiana's specifications for binder material for stabilized bases and the ease of construction association with asphalt emulsions rather than asphalt cements.

The optimal amount of AE 150 to be added to a 100% salvaged material mixture was found to be between 0 and 1%. Additional mixing water had little or no effect on the recycled material's final strength, while curing time had a significant effect on the stability and strength of the recycled mixture.

Indiana's specifications for stabilized bases require that the aggregate gradation of the base material conform to the #53B gradation requirements (nominal top size of 1 inch). Since the gradation of the salvaged bituminous material is nominally 3/4 inch or less, and since the existing base aggregate is nominally 3/4 inches or less, and since a 22% increase in recycled material is required to widen the pavement structure (from 18 to 22

feet), it was determined that 25% new coarse aggregate should be added to the salvaged material. Indiana #4 coarse aggregate, when blended with the salvaged asphaltic material, produced the required #53B gradation. The salvaged material/virgin aggregate blend of 75/25 made it necessary to add 1.13% (residual) of AE 150 to the recycled mixture in order to arrive at the desired optimal asphalt content of 4.5% for the blend. Further testing for water sensitivity indicated that the recycled mixture of virgin aggregate and salvaged asphalt would be very sensitive to the presence of excess water. However, extended curing would significantly increase mixture stability and Hveem cohesiometer values.

4.6 Pavement Design

The final step in the Recycling Guideline process is the determination of the thickness of the recycled pavement layer, as well as other required layer thicknesses. The AASHTO design procedure (see Appendix E) was utilized to determine the required Structural Number (SN) of the reconstructed pavement:

1. Assume a Terminal Serviceability Index - Pt = 2.0
2. Calculate the Daily Equivalent 18 Kip Axle Load utilizing the Design Traffic Number (DTN) previously calculated (see Section 4.1), DTN = 25.5
3. Assume a Soil Support Value - S = 5.0 (see Figure E-1 (V.II))
4. Assume a Regional Factor - R = 1.0 (see Figure E-2 (V.II)).
5. Calculate the required Structural Number - SN = 2.15 (see Figure E-3 (V.II))

The thickness of the recycled material layer will be assumed to be 4-1/2 inches. An AASHTO structural coefficient of 0.22 will be assumed for the recycled material. The subbase, which is the old gravel road materials,

will be assumed to be 4 inches thick with an AASHTO structural coefficient of 0.11. Thus, the combination of subbase aggregate and recycled base material will result in a combined Structural Number of 1.43 (4-1/2 inches X 0.22 + 4 inches X 0.11); equation (E-3 (V.II)). The thickness (D1) of the new material overlay can be determined using the following equation:

$$D1 = \frac{2.15 - 1.43}{a1}$$

where: D1 = thickness of surface layer, new material
2.15 = required structural number of the entire pavement structure
1.43 = structural number of the combined subbase and recycled base
a1 = structural coefficient of the new surface material (assumed to be 0.44 for high stability asphalt concrete mixes)

The equation for D1 yields a value of 1.64 as the required minimum thickness of the new material overlay.

4.7 Summary

Two different rehabilitation alternatives have been identified by the recycling guidelines. The conventional alternative is to widen the pavement from 18 to 22 feet utilizing new materials and balanced widening, construct 4 foot wide shoulders on either side of the travel lanes, reconstruct the side drainage ditches and place a 3 inch new material overlay over the existing pavement surface and the widened pavement. Wedge and level courses will be required at the bridges and railroad crossings.

The recycling alternative that was identified, consists of recycling in-place the existing 4-1/2 inches of asphalt pavement materials. 25% additional virgin aggregate, #4 coarse aggregate gradation, and 1.13% residual asphalt content, AE 150, should be mixed with the salvaged pavement material to construct a 4-1/2 inch thick stabilized base, 22 foot wide. The shoulders should be rebuilt during the recycling process so that 4 foot is provid-

ed on both sides of the pavement. The side drainage ditches should also be reconstructed while the base is being recycled. Vertical transitions at the railroad crossing and bridges should be corrected during recycling. Finally, a 1-3/4 inch thick, 22 foot wide, hot mix asphalt concrete layer should be placed over the recycled base.

CHAPTER FOUR-B

SAMPLE APPLICATION OF CONSTRUCTION GUIDELINES

Application of the Recycling Guidelines to a section of Indiana State Road 32 (see Chapter Four-A) indicated that in-place recycling was a viable rehabilitation alternative. The Guidelines indicated that the 4½ inch thick by 18 foot wide pavement could be satisfactorily recycled, in-place, by adding 25% virgin aggregate and 1.13% (residual) asphalt emulsion to the reclaimed material to construct a 4½ inch thick by 22 foot wide recycled base. A 1-3/4 inch thick by 22 foot wide new material overlay along with 4 foot wide shoulders and side ditch reconstruction completed the pavement design. The focus of this chapter will be on the application of the Construction Guidelines to the recycling process.

4.8 Formulation of a Recycling System

A specific recycling system, composed of the necessary pieces of construction equipment, must be selected for the in-place recycling operations. The characteristics of Indiana State Road 32 greatly influence the choice of equipment. The road is a low traffic volume rural collector, stage-constructed over several decades with materials that have produced a pavement with low material integrity. All of these factors favor the use of conventional, readily available road building equipment. The road favors the prudent selection of equipment that can perform several different recycling operations in order to avoid a proliferation of machines on the job site. Table 3-3 is used as a guide to select the in-place recycling equipment.

4.8.1 Removal

The pavement to be removed is a fairly thick aggregation of stage-constructed materials. However, due to the embrittlement of the binder in the various pavement layers, as evidenced by a low average recovered penetration, and the lower integrity of the stage constructed materials, less effort will be required to loosen and remove this material than would be required of a high grade hotmix material.

The rural nature of the project, the absence of a need for sophisticated grade control during reconstruction, as well as the material characteristics, eliminate the need for selecting a cold miller to remove the existing material. The low type of material associated with the stage-construction favors the use of a sacrifier rather than a ripper. However due to the thickness of the material to be removed, either a scarifier without a full compliment of teeth or a combination ripper-scarifier would be justified.

A motor patrol rather than a crawler tractor would be justified as the prime mover for the scarifier because a lower tractive effort can be tolerated and the selection of the motor patrol would add versatility to the recycling operations. Not only would the motor patrol be able to loosen the pavement material but it could also be used for several other recycling operations.

4.8.2 Crushing and Pulverization

The size of the material loosened by the motor patrol mounted scarifier should be fairly small. Several different types of crushing rollers could be used for pulverization, but all of these machines would require numerous crushing passes. Normally, these types of rollers are used as intermediate processing equipment. The type of material being crushed, as well as the scope of the project, does not justify the use of a multi-shaft stabilizer

for pavement crushing and pulverization.

The single shaft stabilizer would be a good choice for processing the pavement material. Not only would just a few passes of the machine be required to properly crush the salvaged pavement material, but the stabilizer could also be used for the subsequent mixing operation.

4.8.3 Mixing

Production of the recycled material by mixing the salvaged pavement material, the virgin aggregate and the asphalt emulsion could be accomplished by using either a mixer-paver, a windrow mixer, a motor patrol or a single shaft stablizer. Both the mixer-paver and windrow mixer will produce a high quality product. However the degree of quality is not necessary for a base course. Additionally, both mixing devices require additional support equipment.

The motor patrol could be used to blade mix the recycled material. However an asphalt distributor would be required to add the emulsified asphalt to the salvaged material and the mixing action of the blade would not be uniform as needed.

The single shaft stabilizer is a good choice for mixing the recycled material. Not only is the machine already on the job performing the crushing and pulverization, but the machine has the capability to add the emulsified asphalt integrally during the mixing operation. The single shaft stabilizer is capable of producing a mixture in which both the virgin aggregate and the asphalt emulsion is well dispersed in the salvaged material.

The virgin aggregate should be added to the reclaimed material prior to mixing and the addition of the asphalt emulsion. An aggregate spreader, rather than just tail-gating the material out of a rear dump, should be used to insure that the design amount of new aggregate is added to the recycled mixture.

4.8.4 Finishing and Laydown

Although the recycled material could be picked up and placed in a conventional asphalt paver the need for such an action is not justified for base course material. The motor patrol would be the optimal choice for placing the recycled material.

4.8.5 Compaction

Any of the rollers listed in Table 3-3 could be used for recycled material compaction. However, due to the thickness of the recycled lift a vibratory roller operating at a high frequency and amplitude would require fewer passes than a static roller. The vibratory roller would be a good choice for the breakdown and intermediate compaction passes. A pneumatic-tired roller would be a good choice for the finish rolling.

4.8.6 Shaping and Trimming

Since the recycled material is to be used as a base and will be overlain with a 1-3/4 inch new material overlay, shaping and trimming of the recycled material should not be required. However, the motor patrol operated by an experienced operator could adequately provide any trimming that might be needed.

4.9 Recycling System Performance

The performance of the specific in-place recycling system chosen should be evaluated in terms of production, cost and energy consumption. A quantity survey of the materials involved and the scope of the project, prior to system performance evaluation, indicates the following:

Reclaimed Material

3.7 miles x 18 ft wide x 4½ inches thick = 39,000 square yards
= 175,800 sy-in
= 8,790 tons (@100 lb/sy-in)

Recycled Material

3.7 miles x 22 ft wide x 4½ inches thick = 47,750 sy
= 214,900 sy-in
= 10,745 tons (@100 lb/sy-in)

Materials to be added

Aggregate - Indiana #4's
Existing pavement = 450 lbs/sy (assumes 100 lbs/sy-in)
25% Additional Virgin Aggregate = 112 lbs/sy
Aggregate Spreading Rate = 112 lbs/sy

Asphalt Emulsion - AE150 (8.3 lb/gal @ 60°F, 68% min residual)
1.13% (Residual) in recycled mix
Suggested application temperature = 140°F.

$$\text{Application Rate} = \frac{(450 + 112)\text{ lb} \times .0113 \times .98}{8.3\text{ lb/gal} \times .68}$$

$$= 1.10\text{ gal/sy}$$

(.98 = temperature correction factor)

4.9.1 Production

The average production, square yards per hour (sy/hr) is calculated for each recycling operation based on an assumed 45 minute efficiency hour and parameters associated with each component piece of equipment. Daily production is based on an eight hour work day. Total activity duration is calculated by dividing the recycling operation quantity by the average production.

Removal

Equipment - 150 hp motor patrol with combination ripper-scarifier

Working Speed - 88 fpm (1 mph)

Ripping Width - 6 feet

Overlap of Ripping Passes - 50%

$$\text{Ave. Production} = \frac{88 \text{ fpm x } 6 \text{ ft x } .50 \text{ x } 45 \text{ min/hr}}{9 \text{ sf/sy}}$$

= 1320 sy/hr (Table 9-1 reports production range from 800 to 2000 sy/hr)

Daily Production = 10,560 sy

Total Activity Duration = 29.5 hours

Crushing and Pulverization

Equipment - 318 hp single shaft stabilizer - straddle type

Working Speed - 40 fpm

Working Width - 8 feet

Working Dept - 4½ inches

Number of Passes - 3

$$\text{Average Production} = \frac{40 \text{ fpm x } 8 \text{ ft x } 45 \text{ min/hr}}{9 \text{ sf/sy x } 3 \text{ passes}}$$

= 533 sy/hr (Table 9-2 reports production ranges from 400 to 520 sy/hr)

Daily Production = 4267 sy

Total Activity Duration = 73.2 hours

Blading Prior to placement of the virgin aggregate the crushed material must be bladed into proper position to fulfill cross-section demands

Equipment - 150 hp motor patrol

Working Speed - 264 fpm (3 mph)

Working Width - 9 feet

Number of Passes - 2

$$\text{Average Production} = \frac{264 \text{ fpm x } 9 \text{ ft x } 45 \text{ min/hr}}{9 \text{ sf/sy x } 2 \text{ passes}}$$

= 5940 sy/hr

Daily Production = 47,520 sy

Total Activity Duration = 6.6 hours

Aggregate Placement

Equipment - 150 hp aggregate spreader

Working Speed - 176 fpm (2mph)

Spreading Width - 10 ft

Number of Passes - 1

$$\text{Average Production} = \frac{176 \text{ fpm} \times 10 \text{ ft} \times 45 \text{ min/hr}}{9 \text{ sf/sy}}$$

$$= 8800 \text{ sy/hr}$$

Daily Production = 70,400 sy

Total Activity Duration = 4.4 hours

Mixing

Equipment - 318 hp single shaft stablizer, straddle type

Working Speed - 88 fpm (1 mph) (From Table 9-3 working speed ranges from 45 to 100 fpm)

Mixing Width - 8 feet

Number of Passes - 2 (asphalt emulsion to be added during 1st pass)

$$\text{Average Production} = \frac{88 \text{ fpm} \times 8 \text{ ft} \times 45 \text{ min/hr}}{9 \text{ sf/sy} \times 2 \text{ passes}}$$

$$= 1760 \text{ sy/hr}$$

Daily Production = 14,080 sy

Total Activity Duration = 22.2 hours

Laydown - This operation places the recycled material in its final location in the pavement structure

Equipment - 150 hp motor patrol

Working Speed - 264 fpm (3 mph)

Working Width - 9 feet

Number of Passes - 3

$$\text{Average Production} = \frac{264 \text{ fpm} \times 9 \text{ ft} \times 45 \text{ min/hr}}{9 \text{ sf/sy} \times 3 \text{ passes}}$$

$$= 3960 \text{ sy/hr}$$

Daily Production = 31,680 sy

Total Activity Duration = 12.0 hours

<u>Compaction</u> - Breakdown and intermediate

Equipment - 88 hp vibratory roller

Working Speed - 220 fpm (2½ mph)

Compacting Width - 84 inches (7 feet)

Number of Passes - 4

$$\text{Average Production} = \frac{220 \text{ fpm} \times 7 \text{ ft} \times 45 \text{ min/hr}}{9 \text{ sf/sy} \times 4 \text{ passes}}$$

$$= 1925 \text{ sy/hr}$$

Daily Production = 15,400 sy

Total Activity Duration = 24.8 hours

<u>Compaction</u> - Finish

Eauipment - 100 hp, 25 ton pneumatic tired roller

Working Speed 352 fpm (4 mph)

Compaction Width - 84 inches (7 feet)

Number of Passes - 2

$$\text{Average Production} = \frac{352 \text{ fpm} \times 7 \text{ ft} \times 45 \text{ min/hr}}{9 \text{ sf/sy} \times 2 \text{ passes}}$$

$$= 6160 \text{ sy/hr}$$

Daily Production = 49,280 sy

Total Activity Duration = 7.8 hours

4.9.2 Total System Production

More important than calculating individual recycling operation production is calculating total system production. All component pieces of equipment must operate as an integrated system. Normally one type of equipment will control the entire system output, thereby controlling the total recycling system production. A review of the average recycling equipment production previously calculated indicates that crushing and pulverization of the reclaimed material by the single shaft stabilizer, at 533 sy/hr, appears to be the controlling operation. Total system production will depend on reclaimed pavement crushing and pulverization production.

Still another factor to consider is the size of the daily work segment. Although some of the operations, such as ripping and crushing could be accomplished independently of the other recycling operations, most other operations, such as mixing and compaction, must be constrained to such a size so that the total combined operation can be completed in one working day. The size of these daily work segments will affect the total recycling production.

The selection of the size of the daily work segment can be calculated by investigating the maximum size segment each piece of equipment can handle while performing its various recycling operations, as well as looking at combinations of equipment that are dependent on each other. NOTE: work segment size will be based on original pavement dimensions.

<u>Daily Work Segment Size</u> - <u>Motor Patrol Operations</u> - ripping, blading and laydown

$$\text{Work Segment Area} = \frac{8 \text{ hrs}}{\frac{1}{1320 \text{ sy/hr}} + \frac{1}{5940 \text{ sy/hr}} + \frac{1.22}{3960 \text{ sy/hr}}}$$

$$= 6483 \text{ sy}$$

$$= 3240 \text{ lf}$$

Note: 1.22 accounts for the fact that the recycled pavement is 22% wider than the original pavement

<u>Daily Work Segment Size</u> - <u>Single Shaft Stabilizer & Vibratory Roller</u> - crushing, mixing, and compacting

$$\text{Work Segment Area} = \frac{8 \text{ hrs}}{\frac{1}{533 \text{ sy/hr}} + \frac{1}{1760 \text{ sy/hr}} + \frac{1.22}{1925 \text{ sy/hr}}}$$

$$= 2600 \text{ sy}$$

$$= 1300 \text{ lf}$$

It is obvious that if only one single shaft stabilizer and one vibratory compactor is used, the motor patrol will be unproductive for a significant amount of the system time. Therefore, determine the daily work segment size using two single shaft stabilizers for both crushing and mixing, and two vibratory rollers.

<u>Daily Work Segment Size</u> - <u>2 Single Shaft Stabilizers & 2 Vibratory Rollers</u> - crushing, mixing and compacting

$$\text{Work Segment Area} = \frac{8 \text{ hrs}}{\frac{1}{2 \times 533 \text{ sy/hr}} + \frac{1}{2 \times 1760 \text{ sy/hr}} + \frac{1.22}{2 \times 1925 \text{ sy/hr}}}$$

$$= 5200 \text{ sy}$$

$$= 2600 \text{ lf}$$

Based on the preceding analysis look at scheduling equipment and recycling operations based on a daily work segment size of ½ mile or 5280 sy. Shown below is a listing of recycling operations, operation duration and operation interrelationships for ½ mile segments.

Recycling Operation	Operation Duration	Operation Interrelations
Ripping - motor patrol	4.00 hrs	-first operation
Crushing - 2 Single shaft stabilizers	4.95 hrs	-cannot start until ripping has begun
Blading - motor patrol	.90 hrs	-cannot start until ripping completed -cannot finish until crushing completed
Aggregate - aggregate spreader	.60 hrs	-cannot start until blading started -cannot finish until crushing completed
Mixing - 2 single shaft stabilizers	1.5 hrs	-cannot start until crushing completed -cannot start until aggregate started
Laydown - motor patrol	1.65 hrs	-cannot start until 30 minutes after mixing started
Compaction - 2 vibratory rollers	1.70 hrs	-cannot start until 60 minutes after mixing started
Compaction - Pneumatic tired	1.05 hrs	-cannot start until vibratory compaction started -cannot finish until vibratory compaction completed

Figure 4-4 illustrates a typical equipment schedule for ½ mile work segments. Based on the work schedule, total recycling system production is:

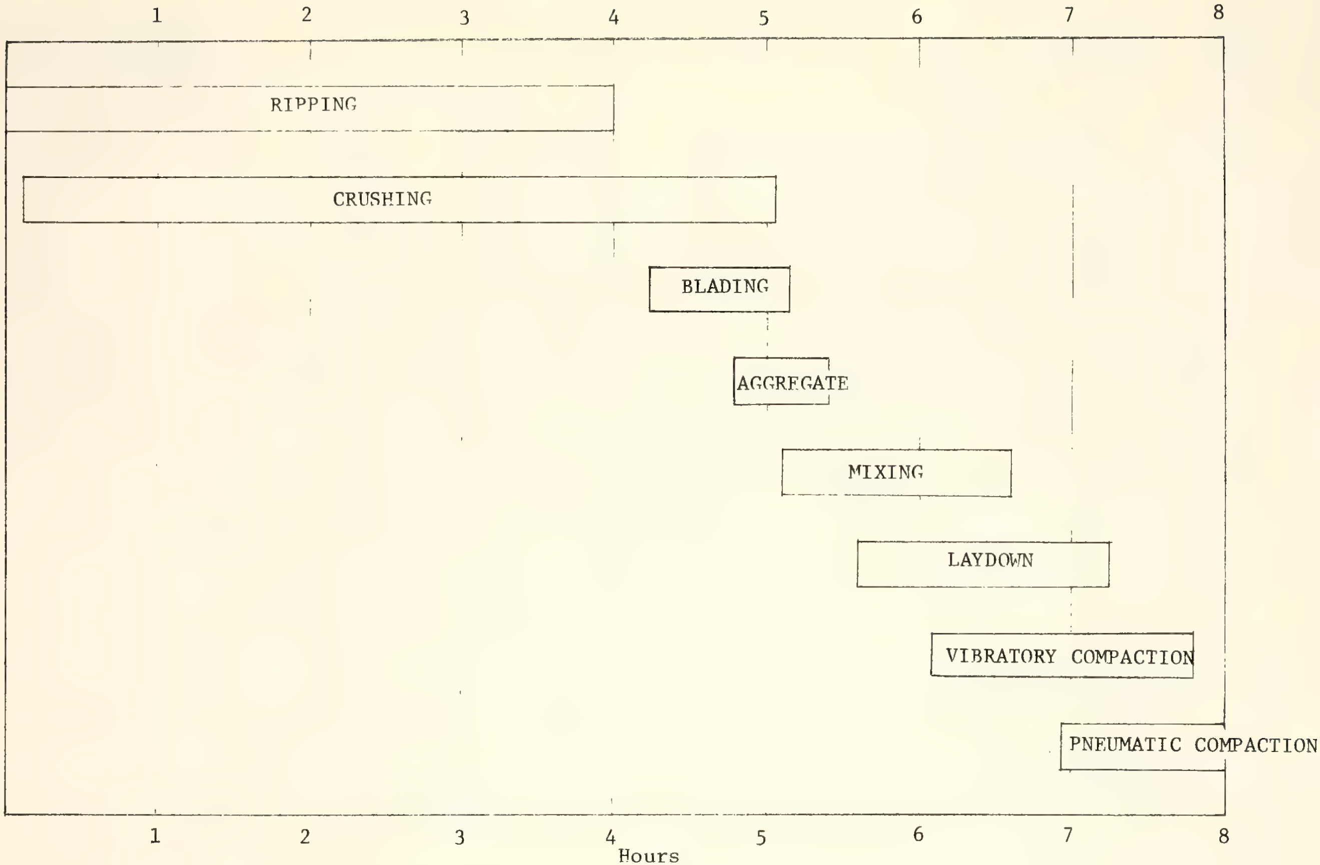
$$\text{Total Project Duration} = \frac{3.7 \text{ miles}}{\frac{1}{2} \text{ mile/work day}}$$

$$= 7.4 \text{ work days}$$

$$\text{Total System Production} = \frac{39{,}000 \text{ sy}}{7.4 \text{ workdays} \times 8 \text{ hrs/day}}$$

$$= 660 \text{ sy/hr} \quad \text{(based on original pavement)}$$

$$= 805 \text{ sy/hr} \quad \text{(based on recycled pavement)}$$



DAILY EQUIPMENT SCHEDULE FOR ½-MILE WORK SEGMENTS

FIGURE 4-4

4.9.3 Costs

The direct costs associated with recycling can be estimated by determining material unit costs, equipment unit costs and labor rates. Profit and indirect expense (mostly general and project overhead), while important, will not be considered.

Materials (based on early 1980 prices in Indiana)

Aggregate - Indiana #4 gradation

$$= \frac{112 \text{ lbs/sy} \times 39{,}000 \text{ sy}}{2000 \text{ lbs/ton}}$$

= 2185 tons

@ \$3.25 / ton = \$7,098

Asphalt Emulsion - Indiana AE 150

1.10 gal/sy x 39,000 sy

= 42,900 gallons

@ \$.50/gal = \$21,450

Total Material Cost = \$28,548

Total Material Unit Cost = \$.72/sy (original area)

= \$.598/sy (recycled area)

Equipment (based on Rental Rate, Blue Book [194] prices - weekly rate + 40 hours. Operators wage based on \$11.75/hr + \$1.30/hr fringe benefit)

Machine	Hourly Rental Rate	Operating Cost	Operator	Total Cost
Motor Patrol	\$40.38/hr	\$15.70/hr	\$13.05/hr	\$69.13/hr
Single Shaft Stabilizer	\$60.38/hr	\$15.65/hr	\$13.05/hr	\$89.08/hr
Aggregate Spreader	\$37.38/hr	\$ 8.75/hr	\$13.05/hr	\$59.18/hr
Vibratory Roller	\$37.50/hr	\$ 8.80/hr	\$13.05/hr	\$59.35/hr
Pneumatic Roller	\$21.12/hr	\$ 5.70/hr	\$13.05/hr	\$39.87/hr

Recycling Operation Costs (based on average machine production)

Motor Patrol

Ripping $= \dfrac{\$\ 69.13/hr}{1320\ sy/hr} = \$\ .052\ /sy$

Blading $= \dfrac{\$\ 69.13/hr}{5940\ sy/hr} = \$\ .012\ /sy$

Laydown $= \dfrac{\$\ 69.13/hr}{3960\ sy/hr} = \$\ .017\ /sy$

Single Shaft Stabilizer

Crushing $= \dfrac{\$\ 89.08/hr}{533\ sy/hr} = \$\ .167\ /sy$

Mixing $= \dfrac{\$\ 89.08/hr}{1760\ sy/hr} = \$\ .506\ /sy$

Aggregate Spreader $= \dfrac{\$\ 59.18/hr}{8800\ sy/hr} = \$\ .007\ /sy$

Vibratory Roller $= \dfrac{\$\ 59.35/hr}{1925\ sy/hr} = \$\ .031\ /sy$

Pneumatic Roller $= \dfrac{\$\ 39.87/hr}{6160\ sy/hr} = \$\ .006\ /sy$

Equipment Minimum Unit Cost = $ .798 /sy

Material Unit Cost = $ .720 /sy

Total Minimum Unit Cost = $1.518 /sy (original area)

Expected Total Recycling Cost = ($465.04/hr x 8 hrs/day x 7.4 days) + $28,548

= $ 56,078.37

Expected Total Recycling Unit Cost = $ 1.44 /sy (Based on original pavement)

= $ 1.17 /sy (Based on recycled pavement)

= $ 0.26 /sy-in (Based on recycled pavement)

4.9.4 Energy

The energy associated with in-place recycling can be calculated by estimating the amount of energy needed to manufacture and transport the new materials in the recycled pavement, as well as the number of gallons of fuel required for recycling equipment operation. Diesel fuel consumption for recycling equipment will be estimated using the rated brake horsepower and the following equation:

$$\text{gallons per hour} - \frac{\text{brake hp} \times .80 \times .42 \text{ lbs/hp-hr}}{7.3 \text{ lbs/gal}}$$

(see section 9.7 Vol. II)

Materials - Energy

Aggregate

Manufacturing - 70,000 btu/ton x 2185 tons = 1.53×10^8 btu

Transportation - 15 miles x 2185 tons x 3800 btu/tm = 1.25×10^8
(assume 15 mile haul)

Asphalt Emulsion

Manufacturing - 42,900 gal x 2100 btu/gal = 0.90×10^8

$$\text{Transportation} - \frac{42{,}900 \text{ gal} \times 8.3 \text{ lbs/gal} \times 50 \text{ miles} \times 3270 \text{ btu/tm}}{2000 \text{ lbs/ton}}$$

(assume 50 mile haul) = 0.29×10^8

Equipment - Energy

Motor Patrol 150 hp	=	6.9 gph x 48.1 hrs	=	331.9 gal
Stabilizer 318 hp	=	14.6 gph x 95.4 hrs	=	1392.8 gal
Aggregate Spreader 150 hp	=	6.9 gph x 4.4 hrs	=	30.4 gal
Vibratory Roller 88 hp	=	4.0 gph x 24.8 hrs	=	99.2 gal
Pneumatic Roller 100 hp	=	4.6 gph x 7.8 hrs	=	35.9 gal
		Total fuel consumption	=	1890.2 gallons

Total Equipment Energy - 1890.2 gal x 139,000 btu/gal = 2.63×10^8 btu

Total Recycling Energy - (materials & equipment) = 6.60×10^8 btu

$$\text{Total Recycled Material Unit Energy Consumption} = \frac{6.60 \times 10^{8} \text{ btu}}{47755 \text{ sy} \times 4\tfrac{1}{2} \text{ inches}}$$

$$= 3071 \text{ btu/sy-in}$$

Table 9-15 (Vol. II) reports in-place recycling energy consumption ranges from 1800 btu/sy-in to 4072 btu/sy-in. Note: this analysis does not include any energy consumed by supervisory or support equipment.

4.10 Pre-Job Analysis

The final task prior to the start of the in-place recycling of SR 32 should be a thorough analysis of the project. The purpose of this pre-job analysis is to identify potential problem areas, as well as construction operations that warrant special consideration during recycling.

4.10.1 Variability

The construction records and to a lesser extent the test pit and the 8 cores taken from SR 32, indicated a variability in the thickness of the bituminous coated aggregate course. In order to validate the estimated material quantities used in the preceding productivity and cost analysis, at least three cored specimens, randomly located, should be obtained from each ½ mile daily work segment.

Since little data is available regarding recycling operation variability, at least 20 randomly selected samples should be obtained from early crushing and pulverization operations, as well as recycled material mixing. The variability of the crushing should be evaluated by determining the average ($\overline{X}$), range (R) and standard deviation (σ) of the amount of material retained on the 2 inch sieve (maximum allowable crushed size) as well as the amount of the material passing the #200 sieve. The variability of the mixing process should be evaluated by determing the variability statistics ($\overline{x}$, R, σ) associated

with the amount of binder in the recycled mix. Compaction variability can be evaluated by conducting in-place density tests using a nuclear density meter.

The variability statistics of the crushing, mixing and compaction operations can be used to develop control charts. The control charts will allow the performance of each of these recycling operations to be evaluated and indicate when corrective actions in the process are needed.

4.10.2 Potential Problem Areas

Table 3-8 in the Construction Guidelines indentifies some of the potential problem areas that might be encountered during in-place recycling.

The use of a combination ripper-scarifier to remove the material to a dept of 4½ inches in ½ mile daily work segments should eliminate most of the ripping problems that might be encountered. The use of single shaft stabilizers for crushing does not require that the reclaimed loosened material be placed in a windrow. These machines should be able to process the reclaimed with little difficulty.

If dispersion of the asphalt emulsion and new aggregate in the reclaimed material becomes a problem during mixing operations, consideration should be given to:

1. Spreading 60 lbs/sy virgin aggregate
2. Adding .55 gal/sy of AE 150 during the first mixing pass with one of the single shaft stabilizers
3. Spreading the remaining 52 lbs/sy of the virgin aggregate
4. Add the remaining .55 gal/sy AE 150 during the second mixing pass using the second single shaft stabilizer

With adequate mixing and blading of the recycled mixture as well as proper timing of the compaction operations no laydown, compaction or trimming problems should be encountered.

4.10.3 Project Management

In order to achieve the in-place recycling production previously calculated timely deliveries of aggregate and asphalt emulsion must be insured. The selection of the size of the daily work segment and scheduling of recycling operations within the work segment should facilitate the actual recycling operations.

While in-place recycling operations are being conducted, through traffic should be detoured around this section of SR 32. Since the road carries such a low volume of traffic,a detour to the north to I-74 using SR 63 on the west and US 71 on the east should pose little problem and inconvenience to the motoring public.

Local traffic can be allowed to use the road during recycling operations. Motorists should be advised to use extreme care and keep speeds down to approximately 15 mph to prevent raveling. If any ripped and crushed material is to be left open overnight or on weekends some compaction should be applied to the reclaimed material to allow local traffic to use the road

4.10.4 Specifications

The guide specifications for in-place recycling, 3.5.5,shall apply to this work.

4.10.5 Summary

A system has been formulated for recycling, in-place, a section of Indiana State Road 32. The existing 18 foot wide pavement is to be ripped using a motor patrol and crushing using two single shaft stabilizers. Additional virgin aggregate, 112 lbs/sy of Indiana #4 gradation aggregate, and additional asphalt, 1.13% (residual) AE 150 asphalt emulsion, is to be mixed

with the crushed pavement material using the two single shaft stabilizers. The recycled material is to be placed in a 22 foot wide stabilized base and compacted with two vibratory rollers and a pneumatic tired roller.

The recycling operations are to be conducted in ½ mile daily work segments. Average hourly recycling system production should be 660 sy/hr (based on original pavement). The expected total recycling unit cost should be $1.17 /sy (based on recycled pavement). Total recycling cost should be $56,078.37. Total recycled material unit energy consumption should be 3071 BTU/sy-in of recycled material.

Through traffic should be detoured around this segment of SR 32. However, local traffic may be allowed on the road during construction if low speeds are maintained and care is exercised by the vehicle operators.

CHAPTER FIVE

SUMMARY

Asphalt pavement recycling is a viable method that can be used to maintain, rehabilitate and reconstruct asphalt pavements. One of the major problems facing transportation agencies is the need to maintain and upgrade the level of service that highways provide, while coping with rapidly escalating costs and a nearly fixed level of highway funding. Asphalt pavement recycling can be a part of the solution to this multi-faceted problem. A significant portion of the highways in this country are constructed with asphaltic materials. Asphalt recycling reuses these materials in the rehabilitation or reconstruction process. As such, recycling not only conserves natural resources, but can be an economical, as well as an energy efficient rehabilitation alternative.

Asphalt pavement recycling is one of many alternative methods that can be used to rehabilitate or reconstruct flexible pavements. However, there are many different ways in which asphalt pavements can be recycled. Basically, asphalt recycling can be classified into three major areas: surface recycling; central plant recycling; and in-place recycling.

5.1 Surface Recycling

Surface recycling, discussed in Chapter 7 (V.II), is one of the most widely used forms of asphalt pavement recycling. This method is primarily used for correcting or rehabilitating the surface layer of flexible pavements. Surface recycling is particularly well suited for treating or

correcting surface deficiencies, as well as pavement geometry problems. A majority of surface related defects can be attributed to the oxidation of the pavement binder that occurs in the upper layer of the pavement surface. Surface recycling either removes this layer of aged material or rejuvenates the material, so that near original binder properties can be restored to the pavement surface. Successive new material overlays can cause problems with vertical clearances, roadway cross-slopes, curb reveal, utility covers and drainage structures. Removing excess surface material, with surface recycling techniques, prior to a new material overlay can eliminate these problems.

Surface recycling can be classified into two major groups: hot surface recycling and cold surface recycling. Hot surface recycling utilizes thermal energy to heat the pavement surface material to facilitate the removal process. Several different machines can be used to accomplish this operation: heater-planers, heater-scarifiers and hot millers. The major problem associated with the use of hot surface recycling techniques is the development of the proper level of thermal energy. Excessive temperature can damage pavement materials, as well as generate excessive atmospheric pollutants. Inadequate temperature can seriously retard the pavement removal process or impede the surface recycling operation.

Cold surface recycling, rather than depending on thermal energy to aid in the pavement removal process, utilizes mechanical energy to plane or mill the pavement surface. The most prevalent type of cold surface recycling equipment is a cold milling machine which utilizes a rotating drum equipped with cutting teeth to remove the pavement surface material. Temperature related degradation of the asphalt binder and associated hydrocarbon emissions are eliminated. In general, cold millers are capable of removing more ma-

terial per pass, with greater cutting accuracy, while consuming less energy per unit of material removed than hot surface recycling equipment.

5.2 Central Plant Recycling

Paving contractors and asphalt producers have shown the most interest in central plant recycling. Central plant recycling, discussed in Chapter 8 (V.II), usually involves removing the existing asphalt-bound pavement material, full depth, and transporting the salvaged material to a central plant where additional new materials may be added to the salvaged materials during a hot mixing operation. The recycled material is then put back on the roadbed with conventional paving equipment. A significant improvement in the structural capacity of the existing pavement can be achieved during this recycling operation. The base/subbase can be reconstructed after the asphalt pavement materials are removed. The salvaged asphalt materials can be rejuvenated and upgraded during central plant mixing operations.

The salvaged material must be crushed and sized prior to recycling in the central plant. Usually, the salvaged asphaltic pavement material is crushed at the central plant site using conventional aggregate crushing equipment, although the material may be crushed in-place, on the roadbed, using mobile equipment.

Central plant recycling can be classified into two major groups: drum mixer recycling and batch plant recycling. The major problem associated with the use of central plant equipment for recycling asphaltic materials is the hydrocarbon emissions that are generated when the salvaged binder is ignited by the dryer flame. Drum mixer recycling utilizes a dual feed process to control hydrocarbon emissions. Uncoated aggregate is used to protect the salvaged asphaltic material from the high temperature of the drum mixer's burner. The uncoated aggregate also acts as a heat transfer medium that

raises the temperature of the salvaged pavement materials. Batch plant recycling also utilizes a dual feed process to eliminate hydrocarbon emissions. Uncoated aggregate is superheated in a conventional dryer, while the salvaged pavement material is introduced directly into the batch plant tower, bypassing the dryer. The salvaged pavement material is heated by the superheated, uncoated aggregate in the batch plant weigh hopper and pugmill, totally eliminating the generation of any hydrocarbon emissions. Modification components or add-on recycling kits are available for both types of central plants so that conventional equipment can be used for central plant recycling.

5.3 In-Place Recycling

In-place recycling is the third major form of asphalt pavement recycling. A variety of equipment and construction techniques can be used to recycled asphaltic pavement materials in-place, see Chapter 9 (V.II). Normally, the product produced by this recycling method is a cold mixed in-place stabilized base. Usually, a new material overlay or an asphalt surface treatment is applied to protect the recycled layer from traffic action, to waterproof the recycled materials and to add increased structural strength to the recycled pavement.

In-place recycling is normally accomplished using conventional road building equipment. Costly transportation operations are eliminated since the asphaltic material is recycled in-place on the roadbed. In-place recycling consumes less energy per unit of material processed than the other two major forms of recycling. The major disadvantage associated with some in-place recycling operations is the inability to control the quality of the product that is produced. Due to the fact that such a wide variety of construction equipment and techniques are used to recycle the materials in-

place, the variability associated with the final product is much greater.

The primary operations required for recycling an asphalt pavement in-place are: removal of the existing pavement; crushing and pulverization of the salvaged pavement materials; mixing of the salvaged material with additional materials (as needed); and laydown and compaction of the recycled product.

Many different types of equipment, ranging from the simple to the relatively complex, can be used to accomplish these operations. The type of new binder incorporated in the recycled mixture will control the type of mixing, laydown and compaction equipment that can be used. The quantity and quality of the existing pavement will dictate, in large part, the proper choice of equipment for removal and crushing operations. The type of equipment chosen, in turn, controls the in-place recycling rate of production, as well as greatly influencing the unit cost associated with recycling operations.

5.4 Recycling Guidelines

The major problem associated with the use of asphalt recycling as a pavement rehabilitation or reconstruction technique is one of determining whether a pavement is a suitable candidate for recycling. The recycling guidelines, outlined in Chapter 2, establish a formal evaluation and investigation procedure that can be used to identify possible recycling candidates.

A pavement investigation program, composed of a field survey program, a historical records investigation and a materials testing program, is used to characterize the existing pavement. The field survey program outlines a formal method for evaluating the existing structure and determining its rehabilitation needs. The geometric adequacy, surface condition and struc-

tural adequacy of the existing pavement is investigated as part of the field survey program. The historical records investigation is conducted using design, construction and maintenance records to determine what should exist in the field. The materials testing program uses field samples to substantiate or refute the findings of the historical records investigation, as well as to characterize the material properties of the existing subgrade, base and bituminous concrete. The existing pavement is fully characterized, and its rehabilitation needs can be identified when the results of the field survey program, the historical records investigation and the materials testing program are combined. These programs also allow the probable cause of pavement distress or failure to be determined. This determination is used to identify feasible alternatives, both recycling and conventional, that can be used to rehabilitate the pavement. The existing condition of the pavement structure, the distress manifestations that are evident in the existing structure and the distress mechanisms producing the problems are all used to identify rehabilitation alternatives.

No quantitative values have been assigned to any of the decision criteria contained within the Recycling Guidelines. It is anticipated that each transportation agency implementing these guidelines will select appropriate values that would be based upon past experience and local conditions. These then could be used to identify the proper rehabilitation alternative(s) for the extent and severity of pavement distress encountered.

The recycling guidelines also comment on mix design procedures that can be used for the major forms of asphalt pavement recycling. Some procedures are outlined for designing recycled mixes that incorporate additional binder, virgin or salvaged base aggregate and reclaiming agents.

Finally, the recycling guidelines comment on the design of the recycled pavement structure. Procedures are outlined so that the proper thickness of the pavement structure, the recycled layer, as well as the conventional material components, can be selected for anticipated traffic and climatic conditions, as well as for the types of materials that will be used.

5.5 Construction Guidelines

A specific recycling system must be selected in order to implement the rehabilitation alternative generated by the recycling guidelines. Construction guidelines, contained in Chapter 3, provide insight and guidance into the process of selecting the component pieces of equipment that will make up the recycling system. The performance of both the system and the system components can be evaluated once the specific recycling system is identified. Anticipated rates of production, unit costs and unit rates of energy consumption should be calculated. The specific recycling system should be compared to an equivalent conventional system on the basis of life cycle costs, total energy consumption and various environmental considerations.

The construction guidelines also provide a means to analyze the proposed recycling project prior to the start of actual construction. Recycling process variability, project management decisions and potential problem areas are identified for the specific recycling system proposed for use.

Finally, guide specifications for the major forms of recycling are provided in the construction guidelines. The forms of recycling that are covered by the specifications are: heater-planing, hot milling, heater-scarification, cold milling, central plant recycling and in-place recycling. The guide specifications are intended to supplement existing specifications or to provide guidance as to how existing specifications should be modified

or revised to account for recycling operations.

CHAPTER SIX

RECOMMENDATIONS FOR FURTHER RESEARCH

This study has identified several areas in which knowledge about recycling operations and recycled products is limited or lacking. Based upon the findings of this study, the areas in which further research should be conducted are:

1. An important influence on recycling costs, particularly cold milling and in-place recycling costs, is the rate at which the existing pavement is removed and/or crushed. A study needs to be conducted that relates variations in pavement composition and material characteristics to removal and crushing production.
2. Preliminary findings seem to indicate that chemicals can be effectively used to assist in crushing and pulverization of salvaged asphalt pavement materials during in-place recycling operations. The cost effectiveness and benefits of such chemical applications should be determined.
3. A major cost associated with cold milling operations and in-place recycling removal and crushing operations is the replacement of fast wear items such as cold miller teeth, stabilizer blades and hammermill hammers. The relationship between pavement characteristics and service life of these fast wear items needs to be determined. A test should be developed which will allow the service life of these items to be accurately predicted.
4. The total cost and energy consumption associated with recycling opera-

tions must be more accurately established. Only limited cost and energy consumption data is available, particularly for in-place recycling operations.

5. Many different types and models of equipment are available for in-place recycling operations. Typically, however, the equipment has not been effectively used. A study should be conducted to relate the types of equipment and the effective use of equipment to the type of pavement materials being recycled. Particular emphasis should be placed on methods that can be used to produce a uniformly recycled mixture, especially with regard to the mixing operation.
6. A majority of the asphalt plants in this country are batch plants which can be readily modified to recycle salvaged asphalt pavement materials. The production of recycled mixtures with small proportions of salvaged materials in the recycled product, which can be easily produced in batch plants, should be thoroughly investigated for use in small quantity operations. Techniques should also be developed which will allow batch plants to produce greater recycled blends than the 50/50 blends that are now the limit. The use of hot exhaust gases to pre-heat the salvaged material stockpile should be further investigated.
7. Strength coefficients should be established for all recycled materials. These coefficients should be suitable for use in pavement design methods, such as the AASHTO method.
8. The long term performance of recycled products must be determined. This information is needed to formulate pavement design strategies using recycled materials, as well as for life cycle costing of recycling operations.
9. Asphalt binder rejuvenators and reclaiming agents need to be studied in

greater detail. The immediate and long term effect of these materials on the recycled pavement materials needs to be documented. A quick test should be developed which will allow the selection of the appropriate rejuvenator for the pavement conditions encountered and the recycling methods chosen.

10. Standardized mix design procedures need to be developed for recycled mixtures, particularly for cold mixed in-place recycled materials.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. AASHO, "AASHO Interim Guide for Design of Pavement Structures-1972", Washington, D.C., 1972.

2. AASHTO Maintenance Manual, first edition, American Association of State Highway and Transportation Officials, Washington, D.C., 1976.

3. A Basic Asphalt Emulsion Manual, The Asphalt Institute, Manual Series No. 19 (MS-19), march 1979.

4. "Aging Freeway Shoulders Recycled in Place", Highway and Heavy Construction, Vol. 121, No. 10, pp. 96, October 1978.

5. Allen, Peters, Ritter, "Characterization of Recycled Bituminous Paving Mixtures to Meet Structural Requirements", A2D04 Committee, Transportation Research Board Meeting, January 1980.

6. America's Highways: Going to Pot, U. S. News and World Report, Vol. 85, No. 3, pp. 36-38, July 24, 1978.

7. "Amsterdam Adds New Life to Old Streets Through Surface Recycling", Paving Forum, pp. 14-15, National Asphalt Paving Association, Winter 1978.

8. Armstrong, Fred., "Can Our Highways Be Saved?" Constructor, Vol. 60, No. 8, pp. 30-34, August 1978.

9. Anderson, D. I., Petersen, D. E., Wiley, M. L., "Evaluation of Selected Softening Agents Used in Flexible Pavement Recycling", FHWA-T5-79-204, April 1978, USDOT FHWA.

10. Anderson, G. S., and Giles, K. T., "Runway Rebuilding With Daily Use", Civil Engineering, Vol. 45, No. 3, March 1975.

11. Annual Report, fiscal year ending 1977, Indiana State Highway Commission, 1978.

12. Ashley, J. F., and Nuss, D. A., "Heater-Scarifier for Pavement Maintenance", Military Engineer, Vol. 66, No. 429, pp. 46:48, Jan./Feb. 1974.

13. Asphalt, The Asphalt Institute, Information Series No. 120, (IS-120), fourth edition, November 1977.

14. Asphalt Cold-Mix Manual, The Asphalt Institute, Manual Series No. 14 (MS-14), February 1977.

15. The Asphalt Handbook, The Asphalt Institute, Manual Series No. 4 (MS-4), April 1965.

16. "Asphalt Industry Eyeing New Ideas for Paving Mixes", Construction Digest, Vol. 51, No. 16, pp. 91-97, September 14, 1978.

17. Asphalt in Pavement Maintenance, Manual Series 16, The Asphalt Institute, 1967.

18. "Asphalt Institute and NAPA Agree on Recycling Definitions", Highway and Heavy Construction, Vol. 120, No. 7, pp. 14, July 1977.

19. Asphalt Overlays and Pavement Rehabilitation, Manual Series No. 17, The Asphalt Institute, 1969.

20. Asphalt Paving Manual, Manual Series No. 8, third edition, The Asphalt Institute, April 1978.

21. "Asphalt Recycled in Place Forms Base for New Pavement", Roads and Streets, Vol. 117, No. 11, pp. 122, November 1974.

22. "Asphalt Recycling Methods for Low-Budget Communities", Rural and Urban Roads, Vol. 17, No. 4, pp. 58-60, May 1979.

23. "Asphalt Recycling Methods Gain Favor in Nevada", Rural and Urban Roads, Vol. 15, No. 2, pp. 32-37, February 1977.

24. Baker, Byrd, and Mickle, "Geometric Design Standards", Handbook of Highway Engineering, Van Nostrand Renhold, New York, 1975, pp. 217-231.

25. Baker, Byrd and Mickle, "Maintenance Procedures", Handbook of Highway Engineering, Van Nostrand Reinhold, New York, 1975, pp. 818-843.

26. Barnes, W. D., Trammell, J. T., Surface Recycling Asphaltic Concrete Pavement-McAllen, Texas, FHWA-DP-39-2, USDOT, August 1978.

27. "The Batch Plant Concept for Recycling", The Barber-Greene Recyclomat System, Barber-Greene Asphalt Construction Conference, 1978.

28. Beckett, Steve, "Demonstration Project No. 39, Recycling Asphalt Pavements", Interim Report No. 1, January 1977, USDOT FHWA.

29. Beckett, S., Clabo, R. J., "Cold Recycling", FHWA-DP-39-13, February 1979, USDOT, FHWA.

30. Bellner, B., "Recycling of Bitminovs Pavements", Highway Focus, Vol. 10, No. 1, pp. 70-76, February 1978.

31. Betenson, Wabe, B., "Recycling Asphaltic Concrete Pavement-SR-26, SR-100 to Holden", Annual Meeting Association Asphalt Paving Technologist, February 1979.

32. Binkley, James K., "Expenditures by Indiana County Highway Depart-

ments", Extension Circular EC 489, 1979, Purdue University, West Lafayette, Indiana.

33. Briggs, Robert C., "Pavement Crushed, Reused to Strengthen Runway Base", Civil Engineering, Vol. 43, No. 4, pp. 82-83, April 1973.

34. Brown, D. J., "Interim Report on Hot Recycling", Recycling Asphalt Pavements, FHWA-DP-39-15, April 1979, USDOT.

35. Bruce, Alan M., "New Life for Old Asphalt", Constructor, Vol. 122, No. 5, pp. 18-21, May 1975.

36. "Build on What you Have", Highway and Hevy Construction, Vol. 122, No. 5, pp. 108-109, May 1979.

37. Byrne, Bob, "New Ideas In Asphalt", Western Construction, pp. 16-20, October 1978.

38. Canessa, William, "Cyclogen for Recycling of Deteriorated Asphalt Pavements Either On-Site or Off-Site", WITCO Chemical Corporation, Golden Bear Division.

39. "Carbide Blades Cut Mixing Costs", Highway and Heavy Construction, Vol. 122, No. 2, pp. 46, February 1979.

40. Carmichael, Terrance, Boyer, Robert E., Hokanson, Lawrence D., "Modeling Heater Techniques for In-Place Recycling of Asphalt Pavements", prepared for 1977 Annual Meeting of the Association of Asphalt Paving Technologist, San antonio, Texas, February 21-23, 1977.

41. Cassell, George A., "California Experiments with Road Recycling", Public Works, Vol. 106, No. 7, pp. 52-53, July 1975.

42. Chang, E. H., "CMI Roto-Mill Pavement Profiler", Highway Focus, Vol. 10, No. 1, pp. 24-39, February 1978.

43. "CMI Makes Public Announcement of Profiling, Recycling Developments", CMI News, Vol. 49, No. 2, pp. 24-27, June 1978.

44. Cohen, N. J., "Statistical Theory in Material Sampling", Journal of the Contruction Division, American Society of Civil Engineers, Vol. 9, No. 001, March 1971, pp. 95-111.

45. "Cold Asphalt Recycling Process Cuts Road Repaving Costs", Engineerin News-Record, Vol. 203, No. 24, pp. 28, December 13, 1979.

46. "Cold Milling Machine Cheaply and Speedily Refurbishes Troubled Dallas Expressway", Civil Engineering - ASCE, Vol. 47, No. 12, December 1977.

47. Coons, R. F., and Wright, P. H., "An Investigation of the Hardening of Asphalt Recovered from Pavements of Various Ages", Proceedings of the Association of Asphalt Paving Technologies, Vol. 37, 1968, pp. 510-528.

48. Cortez, R., "Cold Mix REcycling of Asphalt Pavement in Kansas", Highway Focus, Vol. 10, No. 1, pp. 9-15, February 1978.

49. "Crumbling Roadway is Good as New Without Repaving", Engineering News-Record, Vol. 199, No. 22, pp. 24, December 1, 1977.

50. Dallaire, Gene, "Like to Cut Cost of Repaving Roads 25%?", Civil Engineering, Vol. 43, No. 4, pp. 84, April 1973.

51. Davidson, D. D., Canessa, W., Escobar, S. J., "Single Additive for Recycling Asphalt Pavements", Civil Engineering, Vol. 48, No. 12, pp. 35-38, December 1979.

52. Davidson, Donald D., Canessa, William, and Escobar, Steven J., "The Practical Aspects of Reconstituting Deteriorated Bituminous pavements", Witco Chemical Corporation, Golden Bear Division.

53. Davidson, Donald D., Canessa, William, Escobar, Steven J., "Recycling of Substandard or Deteriorated Asphalt Pavements - A Guideline for Design Procedures", Witco Chemical - Golden Bear Division.

54. "The Declining Prospect for Good Roads", Compressed Air, Vol. 84, No. 1, pp. 8-12, January 1979.

55. DeFoe, J. H., Mixed-in-Place Stabilization of Highway Base Aggregates and Pulverized Bituminous Surfacing Using Asphalt Stabilizers, Research Report No. R-1051, Michigan Department of State Highways and Transportatin, March 1977.

56. Dickson, P. F. and Corlew, J. S., "Thermal Computations Related to the Study of Pavement Compaction Cessation Requirements", Proceedings of the Association of Asphalt Paving Technologists, Vol. 39, pp. 377, February 1970.

57. Dohn, Mark, "North Dakota Gives a Road a Shave", ASSHTO Quarterly, Vol. 56, No. 4, pp. 15, October 1977.

58. Dong, L., "Solving Pollution Problems Using the "Drum-in-a-Drum Concept", Highway Focus, Vol. 10, No. 1, pp. 129-132, February 1978.

59. Doty, R. N., and Scrimsher, T., Recycling Asphalt Concrete on Interstate 80 - Interim Report, FHWA-DP-39-17, USDOT, September 1979.

60. Dumler, J., Beecroft, G., "Recycling of Asphalt Concrete-Oregon's First Hot Mix Project", FHWA-DP-39-4, USDOT, FHWA, March 1979.

61. Dunning, R. L., Mendenhall, R. L., Tischer, K. K., "Recycling of Asphalt Concrete: Description of Process and Test Sections", Asphalt Paving Technology 1975, Vol. 44, pp. 537-562, Proceeding of Association of Asphalt Paving Technologists: Technical Sessions, Phoenix, Arizona, February 10-12, 1975.

62. Elkin, B. L., Evaluation of Recycled Bitminous Pavements, FHWA-DP-39-8, January 1979, USDOT, FHWA.

63. "Emulsion Softener Cuts Resurfacing Costs", Rural and Urban Roads, Vol. 12, No. 9, pp. 48-49, September 1974.

64. Energy Requirements for Roadway Pavements, The Asphalt Institute, MISC-75-3, April 1975.

65. Epps, John A., Guidelines for Recycling Pavement Materials, National Cooperative Highway Research Program, Project No. 1-17.

66. Epps, John A. and O'Neal, Randy J., "Recycling of Pavement Materials", Research Report 214-12, Cooperative Research Project 2-9-74-214, December 1975.

67. Epps, J. A., O'Neal, R. J., and Gallaway, B. M., "A Review of Pavement materials Recycling Techniques and Associated Laboratory Tests and Evaluation", Asphalt paving Technology 1976, Vol. 45, pp. 304-352.

68. Epps, J. A., Terrel, R. L., Little, D. N., "Recycling pavement Materials: An Overview of Alternatives", Part 1 and Part 2, Rural and Urban Roads, Vol. 16, No. 5, pp. 34-36, No. 6, pp. 68-71, May 1971, June 1978.

69. "FHWA Report Calls for Repair of 8,000 Miles of Interstate", Engineering News-Record, Vol. 199, No. 15, pp. 11, October 13, 1977.

70. "Flatiron Sets Recycle Production Record", CMI News, Vol. 50, No. 4, pp. 19-22.

71. Forest Service Handbook, January 1974.

72. Foster, Charles R., "The Annual Cost of Pavements", PS-10, Material Asphalt Paving Association, Riverdale, MD.

73. Frascoia, R. I., Onusseit, D. N., Cold Recycling Asphalt Pavement US Route 4, Sherborn, Vermont, FHWA-DP-39-20, May 1979, USDOT, FHWA.

74. "Fueld Usage in Road Construction", Highway and Road Constructor", Vol. 42, No. 177B, October 1974.

75. Gore, Bill, "Heater-Scarifier, Rejuvenator Cuts Costs of Pavement Overlays", rural and Urban Roads, Vol. 13, No. 10, pp. 32, 35, October 1975.

76. Granley, E. C., "Control Charts", Public Roads, Vol. 35, No. 11.

77. Graley, E. C., "Variations of Bituminous Construction", Public Roads, Vol. 35, No. 10.

78. Green, D., "Surface Recycling in Louisiana", Highway Focus, Vol. 10, No. 1, pp. 87-94.

79. Green Guide, "Road Maintenance", Vol. 2, Equipment Guide-Book Company, palo Alto, California, 1979, pp. 49-75.

80. Haas, Ralph, and Hudson, Ronald, Pavement Management Systems, McGraw-Hill, New York, 1978.

81. "Handbook of Bituminous Compactionology", 1977, American Hoist and Derrick Company, St. Paul, MN.

82. Handbook of Ripping - A Guide to Greater Profits, fifth edition, August 1975, Catepillar Tractor Co., Peoria, Illinois.

83. "Handbook of Soil Stabilization", 1977, American Hoist and Derrick Company, St. Paul, MN.

84. Havers, John A., Stubbs, Frank W., Handbook of Heavy Construction, second edition, McGraw-Hill, New York, 1971.

85. "Heater/Scarifier Saves Money", Highway and Heavy Contruction, Vol. 119, No. 7, pp. 90-91, July 1976.

86. Henely, Richard P., "Evaluation of Air Pollution Control Devices for Asphalt pavement Recycling Operations", Project HR-188 Report Iowa Highway Research Board, December 1977.

87. Henely, R. P., Evaluation of Recycled Asphalt Concrete Pavements, FHWA-DP-39-10, February 1979, USDOT, FHWA.

88. Henry, J. W., Interim Report of Pavement Surface Recycling on Parks Highway Between Little Susitna River and Willow Creek at Willow, Alaska, FHWA-DP-39-5, USDOT, August 1978.

89. Henry, J., "Surface Recycling in Alaska", Highway Focus, Vol. 10, No. 1, pp. 95-105, February 1978.

90. Higgins, Lindley, R., "Remove, Remix and Repave", McGraw-Hill's Construction Contracting, Vol. 60, No. 8, pp. 41-44, August 1978.

91. "Highlights of Transportation Research Meeting - Hot Mix Asphalt Recycling", Civil Engineering, Vol. 49, No. 4, pp. 73-74, April 1979.

92. Highway Statistics, U. S. Department of Transportation, Federal Highway Administration, Annual.

93. "Highway Trust Fund Pressured to pay for More Rehabilitation", Engineering News-Record, Vol. 197, No. 20, pp. 9, Nov. 18, 1976.

94. "Hot Asphalt Recycling-New Roads From Old", Highway and Heavy Construction, Vol. 122, No. 6, pp. 62-681, June 1979.

95. Hughes, C. S., Final Report - Evaluation of Recycled Asphaltic Concrete, FHWA-DP-39-14, February 1979, USDOT, FHWA.

96. Hughes, C. S., "Problems and Solutions to a Hot Mix Recycling Plant", prepared for presentation at 1978 annual meeting of the Association of Asphalt paving Technologists.

97. Hughes, C. H., "Recycling Asphalt Concrete Pavement", Texas DHT 1-9-76-524-1-F, August 1977, Texas SDHPT.

98. Hummel, Joe, District Maintenance Engineer, ISHC, personnel interview, Greenfield, Indiana, June 28, 1978.

99. Ingberg, R. C., Asphalt Recycling in Minnesota, Recycling Asphalt Pavement Seminar - Edmonton, Alberta, Canada, March 1979.

100. Ingberg, Richard C., "Progress Report on Maplewood, Minnesota Recycling Project", Investigation No. 646, Minnesota Department of Transportation, November 1976.

101. Ingberg, Richard C., Morchinek, Richard M., Cassellius, Ronald H., "Minnesota Heat Transfer Method for Recycling Bituminous Pavement", Report on Maplewood, Minnesota Recycling Project, Investigation No. 646, Minnesota Department of Transportation, 1977.

102. Ingberg, Richard C., Morchinek, Richard M., Cassellius, Ronald H., "Progress Report on Recycling Bituminous Shoulders", Special Study 345, Minn. Dept. of Trans., November 1977.

103. "I-75 Absorbs Once-Over From New Profiling Machine", Construction Digest, Vol. 50, No. 23, pp. 14-16, December 22, 1977.

104. "I-75 Cheboygan County Recycling of Asphalt Pavement", Proposed Experimental Work Plan No. 41, Michigan Project 75D-30, Michigan State Highway Commission, May 1975.

105. "Interstate 80 Recycle", AASHTO Quarterly, Vol. 57, No. 3, July 1978.

106. Johnsom, Bruce V., "Cutler Repaving Used in Nevada", Highway Focus, Vol. 10, No. 1, pp. 51-55, February 1978.

107. Jones, George M., "Recycling of Bituminous Pavements on the Road", Annual Meeting Assoc. of Asphalt Paving Technologist, February 1979.

108. Kari, W. J., Santucci, L. E., and Coyne, L. D., Hot Mix Recycling of Asphalt Pavements, Chevron USA, Inc., Presented AAPT Annual Meeting, February 1979.

109. Killmore, D., and Betenson, W., "Bituminous Pavement Recycling in Utah", Highway Focus, Vol. 10, No. 1, pp. 62-69, February 1978.

110. Lawing, Raymond J., "Use of Recycled Materials in Airfield Pavements Feasibility Study", AFCEC-TR-76-7 Final Report, February 1976.

111. Lawton, J., "Asphalt Rejuvenation by Heater-Scarifier", Highway Focus, Vol. 10, No. 1, pp. 56-61, February 1978.

112. LeCierc, R. V., Schermerhorn, R. L., Walter, J. P., Washington State Department of Transportation's First Asphalt Concrete Recycling Project - Renslow to Ryegrass, FHWA-DP-39-3, USDOT, August 1978.

113. Lewis, David R., Production Efficiency Study on Pavement Planning Equipment - Interim Report, Report No. FHWA-DP-PC-1000-1, USDOT, March 1979.

114. Lichtenstein, Grace, "Vital Highway Network Going Downhill Rapidly", New York Times News Service, The Indianapolis Star, June 25, 1978.

115. Lindley, B. R., "Cold Recycling of Asphalt Concrete Pavement", Report No. 613-1, Texas State Department of Highways and Public Transportation, October 1975.

116. Lindley, B. R., Recycling Asphaltic Concrete Pavement, FHWA-DP-39-11, March 1979, USDOT, FHWA.

117. "Low Profile Scarifi . Trims Tunnel Roadways", Highway and Heavy Construction, Vol. 120, No. 5, pp. 114-115, May 1977.

118. Luettich, Richard A., "The 3-R Program: Monster or Saint", AASHTO Quarterly, Vol. 57, No. 1, pp. 14-15, January 1978.

119. Mandy, J., and Wolfgram, V. H., "Milling Bitumious Surfacing in North Dakota", Highway Focus, Vol. 10, pp. 40-50, February 1978.

120. Materials for Stabilization, Education and Information Guide, American Road builders Association, September 1976.

121. "Maplewood Pavement Recycling Project Demonstrates New Approach", Paving Forum, national Asphalt Paving Association, pp. 3-6, Winter 1976.

122. "Material Prices", Engineering News-Record, Monthly.

123. McGee, James A., Judd, A. James, "Recycling of Asphaltic Concrete - Arizona's First Project", Arizona Department of Transportation.

124. "A Method for Rating the Condition of Flexible Pavements", Highway Research Correlation Service Circular 476, Highway Research Board, August 1962.

125. Meyer, A. H., Ledbetter, W. B., Layman, A. H., Saylak, D., "Reconditioning Heavy-Duty Freeways in Urban Areas", National Cooperative Highway Research Program, Report 196, Transportation Research Board, 1978.

126. Michael, Harold L., "Highways Are Not Eternal", Legislative Breakfast Conference, Indianapolis, IN, January 10, 1979.

127. Milling Bituminous Surfaces - Ellendale, North Dakota, FHWA-DP-39-7, USDOT, September 1978.

128. "Mill 18 City Streets in 18 Days", Better Roads, Vol. 47, No. 9, September 1977.

129. Minor, W. H., "CMI 1979 Recycling Review", CMI News, Vol. 50, No. 6,

pp. 11-15, December 1979.

130. "Missouri Recycling Project Becomes A Show Race Demonstration", Rural and Urban Roads, Vol. 17, No. 6, pp. 82-83, June 1979.

131. "Model Specifications", Asphalt Recycling and Reclaiming Association.

132. Moore, W. M., Hansom, D. I., and Hall, J. W., "An Introduction to Nondestructive Structural Evaluation of Pavements", Transportation Research Circular No. 189, January 1978, Transportation Research Board.

133. Mosley, John R., and DeFoe, J. H., In-Place Recycling of Asphalt Pavements, Annual Meeting Association of Asphalt paving Technologists, February 1979.

134. Myers, David E., "In-Place Recycling/Reconstruction of Flexible Pavements", presented to the Canadian Technical Asphalt Association, November 21, 1977.

135. "NAPA Annual General Meeting - Recycling, New Market", Highway and Heavy Construction, Vol. 122, No. 4, pp. 88-90, April 1979.

136. "NAPA Publication Defines Asphalt Material Recycling", Construction Digest, Vol. 50, No. 11, pp. 65, July 7, 1977.

137. NAPA Recycling Report, National Asphalt Pavement Association, Vol. 1, No. 1, May 1977.

138. NAPA Recycling Report, National Asphalt Pavement Association, Vol. 2, No. 3, December 1977.

139. NAPA Recycling Report, National Asphalt Pavement Association, Vol. 2, No. 1, January 1978.

140. NAPA Recycling Report, National Asphalt Pavement Association, Vol. 2, No. 2, March 1978.

141. NAPA Recycling Report, National Asphalt Pavement Association, Vol. 2, No. 2, March 1978.

142. "Nation's Roads Deteriorating Rapidly", Engineering News-Record, Vol. 199, No. 19, pp. 14, November 10, 1977.

143. "Nevada Recycles a Highway", Paving Forum, pp. 4-7, Winter 1974.

144. "New Cool Way to Restore Blacktop", Highway and Heavy Construction, Vol. 119, No. 5, pp. 137-138, May 1976.

145. "New Machine Shaves Ruts", Highway and Heavy Construction, Vol. 121, No. 2, pp. 65-67, February 1978.

146. "New Orleans Saves Streets with Planning, Hot Mix Overlay", Paving Forum, Winter 1974, pp. 13-14.

147. Nichols, H. L., Jr., Moving the Earth, third edition, North Castle Books, Greenwich, Connecticut, 1976.

148. Nichols, J., "Salvaging and Recycling Bituminous Materials (Hot)", Highway Focus, Vol. 10, No. 1, pp. 77-86, February 1978.

149. "Ninety Three Million Holes in the Road for Angry Drivers", U. S. News and World Report, Vol. 86, No. 12, pp. 78-79, March 19, 1979.

150. "North Dakota Mills Roadway to Eliminate Slippery Conditions", Better Roads, Vol. 47, No. 9, September 1977.

151. "Old Asphalt Can Be Valuable Raw material", Roads and Streets, Vol. 117, No. 6, pp. 105-106, June 1974.

152. "Old Overlay Ground Off in Texturing Pass", Highway and Heavy Construction, Vol. 121, No. 4, pp. 26-27, April 1978.

153. "Old Overlay Removed, New Overlay Placed Fast", Highway and Heavy Construction, Vol. 120, No. 10, October 1977.

154. "Old Roads Never Die, They Just Are Recycled", Civil Engineering, Vol. 48, No. 12, pp. 76, December 1978.

155. O'Neil, Verde, personnel interview, Rieth-Riley Construction Company, South Bend, Indiana, July 25, 1978.

156. Ortgies, Bernard, "Asphalt Recycling With a Twist of Sprinkled Stone", Rural and Urban Roads, Vol. 16, No. 1, pp. 20-22, January 1978.

157. Ortgies, Bernard H., "Recycling of Cass County I-80 Asphalt concrete", Progress Report for HR-1011, Iowa Department of Transportation, October 1977.

158. Packer, Mal M., and Whitney, Gordon F., "Cold Planning Takes Heat Off Asphalt Runway Resurfacing", Roads and Streets, Vol. 118, No. 7, July 1975, pp. 84-87.

159. Parsons, Frank, "Recycling-In Place Recycling SR 32", 3rd Annual Indiana Asphalt Paving Conference, Indianapolis, Indiana, March 27, 1979.

160. Pavement Planning Speeds Up Milwaukee's Resurfacing Program", Rural and Urban Roads, Vol. 14, No. 12, pp. 38-39, December 1976.

161. "A Pavement Rating System For Low Volume Asphalt Roads", I. S. 169, November 1977, Asphalt Institute, College Park, Maryland.

162. "Pavement Recycling Market Emerging", Construction Digest, Vol. 51, No. 6, pp. 66-70, April 27, 1978.

163. Pavement Rehabilitation Materials and Techniques, NCHRP Synthesis of Highway Practice 9, Highway Research Board, 1972.

164. "Pennsylvania Turnpike Profiles Prior to Overlay", CMI News, Vol. 15,

No. 1, pp. 7-9, January 1979.

165. Personnel Correspondence and Literature, Gordon Cobb, Indiana Highways for Survival, Indianapolis, Indiana, January 24, 1979.

166. Personel Correspondence, Donald S. Knight, TRIP - The Road Information Program, Washington, D. C., January 17, 1979.

167. Personal Interviews and Project Observations, Indiana State Route 32 Recycling, Fountain Company, Indiana, September 20-25, 1978.

168. Personnel Interviews and Project Observations, Interstate 75 Recycling, Osceola County Michigan, August 1-2, 1978.

169. Personnel Interviews and Project Observations, Kern Road Recycling, St. Joseph County, Indiana, August 15, 1979.

170. Personnel Interviews and Project Observations, Washington and Adams Streets, Marion, Indiana, April 30, 1979.

171. Peterson, J. C., Barbour, F. A., and Dorrence, S. M., "Catalysis of Asphalt Oxidation by Mineral Aggregate Surfaces and Asphalt Components", Proceedings of Association of Asphalt Paving Technologists, Vol. 43, 1974, pp. 162-177.

172. Phegley, Richard, District Maintenance Engineer, ISHC Personnel Interview, Vincennes, Indiana, July 11, 1978.

173. Phillips, David L., "Reclamation Process Cuts Street Construction Costs by 35%", The american City, Vol. 88, No. 3, pp. 67-68, March 1973.

174. "Planer-Key to Street Recycling", Roads and Streets, Vol. 118, No. 1, pp. 606-1, January 1975.

175. Potts, Charles F., and Murphy, Kenneth H., Surface Recycling of Asphalt Concrete Pavements, FHWA-DP-39-22, USDOT, September 1979.

176. "Principal Provisions of the Surface Transportation Assistance Act", American Transportation Builder, Vol. 55, No. 6, pp. 13-18, November/December 1978.

177. Profiling Book, CMI Corporation, January 1979.

178. "Quarterly Cost Roundup", Engineering News-Record, Quarterly.

179. Rand, D. W., "Cold Recycling of Pavement by Hammermill Process - Interim Report", FHWA-ME-TP-77-10, August 1977, USDOT, FHWA.

180. Rand, D. W., Cold Recycling of Pavement Using the Hammermill Process, FHWA-DP-39-24, March 1979, USDOT, FHWA.

181. "Rebuild to Cut Maintenance Cost", "Rebuild to Cut Maintenance Cost", Rural and Urban Roads, Vol. 5, No. 3, Page 35, March 1967.

182. "Recycled Materials Rejuvenate Rural Roads", Roads and Streets, Vol. 118, No. 10, pp. 114, 116, October 1975.

183. "Recycling", Construction Digest, Vol. 51, No. 27, pp. 20-38, February 15, 1979.

184. "Recycling Asphalt Clears Air, Cuts Costs", Highway and Heavy Contruction, Vol. 120, No. 11, pp. 90-94, November 1977.

185. "Recycling-Big Potential But Still Questions", Highway and Heavy Contruction, Vol. 120, No. 5, pp. 162-163, May 1977.

186. Recycling Book, CMI Corporation, January 1979.

187. "Recycling Group - Give Use Better Tools and Standards", Rural and Urban Roads, Vol. 17, No. 11, pp. 44, November 1979.

188. "Recycling Materials for Highways", Synthesis of Highway Practice, No. 54, National Cooperative Highway Research Program, 1978.

189. "Recycling of Asphaltic Concrete Pavements - Laramie, Wyoming, FHWA-DP-39-9, USDOT, February 1979.

190. "Recycling Old Asphalt", Rural and Urban Roads, Vol. 13, No. 3, March 1975.

191. "Recycling Old Base and Surface Warms Up City's Hot Mix Paving", Rural and Urban Roads, Vol. 17, No. 1, pp. 22-23, January 1979.

192. "Recycling - The Future is Now", Proceedings-Workshop Session, National Asphalt Paving Association, 23rd Annual Convention, February 1978.

193. "Recycling the Hot Mix Way! What Texas and Oregon Learned", Rural and Urban Roads, Vol. 16, No. 7, pp. 30-32, July 1978.

194. Rental Rate Blue Book, "Asphalt and Bituminous Equipment", Equipment Guide-Book Company, Palo Alto, CA, 1979, pp. 29-34.

195. "Reprocessed Asphalt Gets First Highway Test", Roads and Streets, Vol. 117, No. 12, pp. 28-30, December 1974.

196. "Rescue Stalled Tunnel Job", CMI News, Vol. 49, No. 3, pp. 27-29, october 1978.

197. "Resurface Central Avenue with Milling Machine", Highway and Heavy Construction, Vol. 119, No. 2, pp. 53-54, February 1976.

198. "Reusing Oil Surfacing Saves County $300,000", Rural and Urban Roads, Vol. 14, No. 3, pp. 44, March 1976.

199. Riedl, P., "Recycling Asphalt Pavements in Oregon", Highway Focus, Vol. 10, No. 1, pp. 106-118, February 1978.

200. Ritter, John, Pavement Recycling Project - 18 Yuma County Line - Gila

Bend, FHWA, DP-39-16, USDOT, May 1979.

201. "Revolution in Paving Counters Rising Costs", Engineering News-Record, Vol. 202, No. 10, pp. 22-24, March 8, 1979.

202. "Road Planer Cuts Resurfacing Time", Engineering News-Record, Vol. 197, No. 15, pp. 26-27, October 7, 1976.

203. "Road Planer Tapers a Runway", Engineering News-Record, Vol. 198, No. 15, pp. 57, April 14, 1977.

204. "Road Regraded by Planer", Highway and Heavy Contruction, Vol. 122, No. 2, pp. 86, February 1979.

205. "Roto-Cycler Joins Roto-Mills for First California Hot Mix Recycling", CMI News, Vol. 49, No. 3, pp. 8-11, October 1978.

206. "Roto-Mill, PDM-936, Clarco Team Up on Rocky Mountain Tunnel Resurfacing", CMI News, Vol. 15, No. 1, pp. 11-13, January 1979.

207. "Roto-Mill PR-225 Proves "Perfect" for Syracuse Streets", CMI News, Vol. 49, No. 3, pp. 16-18, October 1978.

208. "Roto-Mill PR-225 Recycles California City Streets", CMI News, Vol. 49, No. 3, pp. 19-21, October 1978.

209. "Roto-Mills Set Recovery Record", CMI News, Vol. 49, No. 3, pp. 12-15, October 1978.

210. "Roto-Mill Speeds Shoulder Repair", CMI News, Vol. 50, No. 2, pp. 10-11, May 1979.

211. Sargent, H. Jack, Recycling 50 Miles of Bituminous Pavement Saves Dollars - Expands Road Program, Proceedings of the 63rd Annual Road School, March 1977, Purdue University, Series No. 148.

212. Scherr, G. F., "Pavement Removal Using CMI 750 Roto-Mill", Highway Focus, Vol. 10, No. 1, pp. 22-23, February 1978.

213. Simanski, Robert E., "Cold-Mix Asphalt Recycling in Binghampton, New York", Highway Chemicals Newsletter, Armack, Summer 1979.

214. "Skid Resistance, Recycled Asphalt Get Joint Fed-State Test", Rural Urban Roads, Vol. 13, No. 7, pp. 18-19, July 1975.

215. Smith, Clarence W., In-Place Recycling of Asphalt Pavement - Republic County, Kansas, FHWA-DP-39-1, USDOT, August 1978.

216. Smith, R. W., "Considerations for Producing Quality Recycled Hot-Mixed Asphalt", NAPA Special Report, April 1977.

217. Smith, Richard W., "A Summer of Recycling", Paving Forum, pp. 5-9, National Asphalt Paving Association, Winter 1978.

218. "Sound Waves Power Asphalt Grader's Cutting Blade", Engineering News-Record, Vol. 201, No. 22, pp. 33, November 30, 1978.

219. "Stabilization: Exacting Art, Road Building Bagain", Highway and Heavy Construction, Vol. 122, No. 2, pp. 30-33, February 1979.

220. "Standard Equipment Makes Old Road New", Highway and Heavy Construction, Vol. 122, No. 2, pp. 34-35, February 1979.

221. Standard Nomenclature and Definitions for Pavement Components and Deficiencies, Special Report 113, Highway Research Board, 1970.

222. "Surface Recycling of Asphalt Pavements by the Heater-Overlay Process", MISC-77-3, The Asphalt Institute, June 1977.

223. Swisher, W. E., "Roads and Bridge Neglect - America's Next Great Crisis", American Transportation Builder, Vol. 55, No. 6, pp. 4-11, November/December 1978.

224. "Taking it From the Top", Proceedings - Workshop Session, National Asphalt Paving Association, 23rd Annual Convention, February 1978.

225. Taylor, N. H., "Life Expectancy of Recycled Asphalt Paving", Recycling of Bituminous Pavements, ASTM Special Technical Publication 662, Wood, L. E., Editor, American Society for Testing and Materials, 1978, pp. 3-15.

226. "Texas Asphalt-Aggregate Recycling Efforts", AASHTO Quarterly, Vol. 56, No. 2, pp. 32, April 1977.

227. "Theres Life in That Old Pavement Yet", Michigan tractor and Builder, August 2, 1975.

228. Thickness Design, The Asphalt Institute, Manul Series No. 1 (MS-1), August 1970.

229. "This is the Story of Asphalt - Maintenance", Jim Jackson Contractor, Little Rock, Arkansas.

230. Thomas, Larry W., "Up Against the Law", Construction Digest, Vol. 51, No. 9, pp. 87-102, June 8, 1978.

231. Tia, Mang, "A Laboratory Investigation of Cold-Mixed Recycled Bitunimous Pavements", Interim Report, Joint Highway Research Project, Purdue University, December 1978.

232. "Tooth Wear Sets Pace for Pavement Planer", Highway and Heavy Construction, Vol. 122, No. 7, pp. 98-99, July 1979.

233. Vyce, John M. and Nittinger, Robert J., "Milling and Planing of Flexible Pavement Paper Presented to 56th Annual Meeting of the Transportation Research Board, Washington, D. C., January 24-28, 1977.

234. Walton, C. and Levien, D., "Recycling of Asphalt Concrete in Washing-

ton", Highway Focus, Vol. 10, No. 1, pp. 119-128, February 1978.

235. Wang and Rafalowski, "Cold Recycling of Asphalt Concrete", Highway Focus, Vol. 10, No. 1, pp. 1-9, February 1978.

236. Webb, James, Albritton, Gayle, Chance, Thomas, Surface Recycling of Asphalt Concrete Pavement (Progress Report), FHWA-DP-39-12, USDOT, March 1979.

237. Whitney, Gordan, "Public Relations Engineering Simplifies Downtown Resurfacing", Western City Magazine, November 1970.

238. Williams, Clyde E. and Associates, Inc., "Summary Report: 1976-1995 Indiana Highway Needs Study", November 1976, South Bend-Indianapolis, Indiana.

239. Williams, Ellis G., "Asphalt Recycling: A Dollar-Stretching Way to Improve Pavement", The Asphalt Institute, MISC-78-2, May 1978, pp. 6.

240. Wolters, Richard O., Bituminous Hot Mix Recycling in Minnesota, Presentation Annual Meeting, Assoc. of Asphalt Paving Technologist, February 1979.

241. Yoder, E. J. and Witczack, Principles of Pavement Design - 2nd edition, Wiley-Interscience, 1975.

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